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# A Comparative Study on Micro Electro-Discharge Machining of Titanium Alloy (TI-6AL-4V) and Shape Memory Alloy (NI-TI)

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A COMPARATIVE STUDY ON MICRO ELECTRO-DISCHARGE MACHINING OF  
TITANIUM ALLOY (TI-6AL-4V) AND SHAPE MEMORY ALLOY (NI-TI)

A Thesis  
Presented to  
The Faculty of the Department of Architectural and Manufacturing Sciences  
Western Kentucky University  
Bowling Green, Kentucky

In Partial Fulfillment  
Of the Requirements for the Degree  
Master of Science

By  
Pegah Kakavand

May 2015

A COMPARATIVE STUDY ON MICRO ELECTRO-DISCHARGE MACHINING OF  
TITANIUM ALLOY (TI-6AL-4V) AND SHAPE MEMORY ALLOY (NI-TI)

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Dean, Graduate Studies and Research      Date

I dedicate this thesis to my parents, Mahin and Mahmud Kakavand, who are a great inspiration to me. I also, dedicate this thesis to my lovely brother, Parsa.

## ACKNOWLEDGMENTS

I would like to express my gratitude to my supervisor, Dr. Muhammad Jahan, whose understanding and patience, added considerably to my graduate experience. My sincere thanks also go to Dr. John Anersland, Dr. Edwin Stevens, Dr. Mark Doggett, and Dr. Bryan Reaka for leading and helping me work on my project. Sincere thanks to my family and friends: Mahmud Kakavand, Mahin Kakavand, Parsa Kakavand, Bright Adu, Kianoosh Ebrahimi and Mychal-Drew Moses.

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# A COMPARATIVE STUDY ON MICRO ELECTRO-DISCHARGE MACHINING OF TITANIUM ALLOY (Ti-6Al-4V) AND SHAPE MEMORY ALLOY (Ni-Ti)

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The purpose of this research was to investigate the surface modifications that take place during the machining of NiTi SMA and Ti-6Al-4V with micro-EDM. This was done by creating an array of blind holes and micro-patterns on both work-pieces. To analyze the machined surface and investigate the results, scanning electron microscope (SEM), energy dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD) techniques were employed. In addition, the effects of various operating parameters on the machining performance was studied to identify the optimum parameters for micro-EDM of NiTi SMA and Ti-6Al-4V.

Recently, aerospace and biomedical industries have placed a high demand on non-conventional machining processes, which can be used to machine high strength and hard-to-cut materials such as Titanium alloys, Shape Memory Alloys (SMA) and Super Alloys. Electrical Discharge Machining (EDM) is one of the non-traditional technologies that remove materials from the workpiece through a series of electrical sparks that occur between the workpiece and cutting tool with the presence of dielectric liquid.

Obtaining smooth and defect-free surfaces on both workpieces was one of the challenges due to the re-solidified debris on the machined surface. The experimental results showed that there was significant amount of re-casting and formation of re-solidification of debris on the Ti surface after machining. On the other hand, the surface

generated in NiTi SMA were comparatively smoother with lesser amount of resolidified debris on the surface. By analyzing the results from XRD and EDS, some elements of electrode and dielectric materials such as Tungsten, Carbon and Oxygen were observed on NiTi and Ti surface after machining.

In the study of effect of operating parameters, it was found that the voltage, capacitance and tool rotational speed had significant effect on machining time. The machining time was reduced by increasing the voltage, capacitance and tool rotational speed. The machining time was found to be comparatively higher for machining NiTi SMA than Ti alloy. Comparing all the parameters, the voltage of 60 V, capacitance of 1000 PF, and tool rotational speed of 3500 RPM were selected as optimum parameters for this study.

Although signs of tool electrode wear and debris particles on the machined surface were observed for both workpieces during the micro-EDM process, Ti alloy and NiTi SMA could be machined successfully using the micro-EDM process.

## **Introduction**

In recent years, manufacturing industries are in need of hard and difficult-to-cut materials for various important applications. Some of the common difficult-to-cut materials are Titanium based alloys, Nickel based alloys, and Shape Memory Alloys (SMA), that are found to be used extensively in aerospace and biomedical industries. The conventional machining processes are difficult for machining of these hard-to-cut materials because of their specific properties such as high strength-to-weight ratio, high resistance to wear, and poor electrical and thermal conductivities. As a result, non-conventional machining processes with comparatively higher accuracy are introduced. Electro-Discharge Machining (EDM) is one of the most widely used non-conventional machining processes for machining hard and difficult-to-cut materials (Jahan, Rahman & Wong, 2011).

EDM is for machining conductive workpiece materials in order to remove material from the workpiece surface. This method is typically used in modern manufacturing industries such as the automobile and aerospace industry. The basic principle of EDM is that it removes materials from the workpiece through a series of electric sparks that occur between the workpiece and cutting tool (Ndaliman, Khan & Ali, 2013). The electrical energy is transformed into thermal energy through a series of discrete electrical discharges between the electrode and work piece. This thermal energy is absorbed in a dielectric liquid medium (Pandey, 2010).

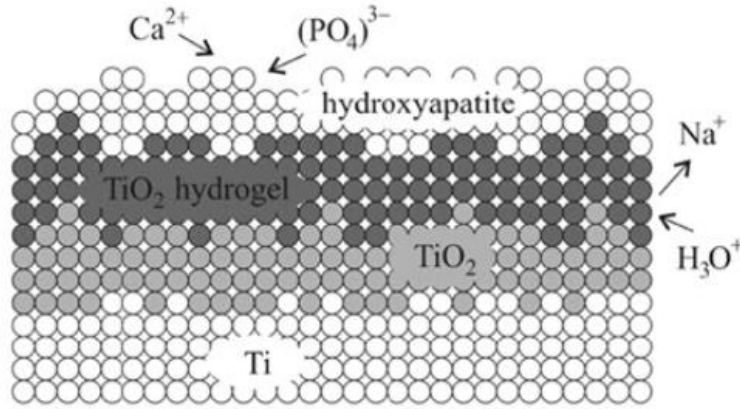
Because of the recent advances in modern manufacturing technology of micro-electro mechanical system (MEMS), a new generation of EDM, micro-EDM has been developed. The micro-EDM is the miniaturized technology of EDM to the sub-millimeter

level. The main principle of micro-EDM is the same as the EDM process, but, with a different power, discharge energy and size of tools (Kibria & Bhattacharyya, 2010).

SMA and Titanium alloys are two difficult-to-cut and difficult-to-machine materials because of their specific properties. For example, NiTi SMA has high wear resistance, shape recovery capability, stress hysteresis, super elasticity, and magnetic resonance imaging (MRI) compatibility properties which are caused to be useful in biomedical applications. In addition to SMA, Titanium alloys are employed in various applications such as in micro-engineering, aerospace, and automotive industries because of excellent properties. Similarly, Titanium alloy is commonly used in biomedical industries as orthopedic implants because of the excellent corrosion resistance, lightweight and mechanical properties. SMA is used in medical technology as an endodontics for wires, orthodontic arch-wires, and endoscopic instruments to endovascular stents (Alidoosti, Ghafari, Moztarzadeh, Jalali, Moztarzadeh & Mozafari, 2013).

The human body is an intricate electrochemical system that creates an aggressive corrosion environment for metallic implants. The body fluids (includes 0.9 % NaCl, organic compounds and a small amounts of other salts) cause corrosion to metallic implants. Body fluids have high acidity that could be a serious threat for metallic implants. Many researchers have done studies on the cytotoxicity of Nickel and Titanium that showed that it is less harmful to the bone structure as compared to other implant alloys such as cobalt or vanadium. Also, Titanium can create a stable Titanium Oxide layer on its surface and has the ability of excellent osseointegration with the bone in an optimal situation. It is known as one of the most biocompatible materials in the

biomedical industry (Machado & Savi, 2003; Key to Metals A.G., 2009). Generally, Titanium prevents corrosion from hydroxyapatite and is capable of producing a calcium phosphate-rich layer on its surface, as shown in Figure 1.



*Figure 1.* Formation of hydroxyapatite layer on titanium oxide film (Key to Metals A.G., 2009)

However, being electrically conductive, NiTi SMA and Ti are found to be comparatively easier to machine by the micro-EDM process. Therefore, this investigation will provide an insight into the micro-EDM behavior of NiTi SMA and Ti as well as surface modification process and its effect on mechanical properties of the materials. Hence, to work with these kinds of hard-to-cut materials, micro-EDMs are used to obtain higher material removal rate (MRR), accuracy and good surface finish with less tool wear rate (TWR). Reaching to the integrity surface after machining is one of the important results in manufacturing and machining process (Shabgard, Oliaei, Seyedzavvar & Najadebrahimi, 2011). Thus, the first phase of this research was investigating the surface finish, the surface modification and property changes after micro-EDM of NiTi SMA and Titanium alloy. The second phase was analyzing the machinability of micro-EDM in terms of machining time.

## **Significance of the Research**

Parts fabricated using the SMAs and Titanium alloys are primary used for biomedical applications. SMAs that are used as implants can be harmful and dangerous for the human body. This research attempted to identify different elemental composition materials and any harmful substances on the machined surface in order to remove or reduce those that are not biocompatible. This research also investigated the feasibility of using micro-EDM process for machining biomedical implants in these two materials. If the machined surface was found to be biocompatible, then micro-EDM can be a suitable option for machining these extremely hard and difficult-to-cut materials.

## **Purpose of the Research**

The purpose of this research was to investigate micro-EDM induced surface modification and property changes to NiTi shape memory alloy (SMA) and Ti-6Al-4V Titanium alloy. The aim of this research was to find the formation of different compounds on the machined surfaces after the micro-EDM process and compare the surface of these two workpieces. The machined surface was analyzed using the Scanning Electron Microscope (SEM), the Energy Dispersive X-ray Spectroscopy (EDS) and X-ray Diffraction (XRD) techniques. The result obtained from the EDS and XRD techniques may indicate the formation of thin surface coating on the machined surface. Further investigation was carried out to minimize the surface modification and to reduce the changes in mechanical properties of the materials after the micro-EDM process.

The second phase of this research focused on finding the optimal parameter settings for micro-EDM of Ti-6Al-4V and NiTi SMA, so that industries can design machining operations to meet their needs. The identification of optimal parameter



settings is based on mostly the machining time and surface finish, which affects the future usefulness and performance of a product. In this study, various operating parameters from a Resistance-Capacitance (RC) type pulse generator, such as: voltage, capacitance, and tool rotational speed (revolutions per minute, RPM) were varied to identify the optimal parameter settings.

### **Research Questions**

1. Does NiTi SMA have a better surface quality than Ti?
2. Do Ti and NiTi SMA have a biocompatible surface finish with micro-EDM?
3. Can micro-EDM successfully machine Ti and NiTi SMA?
4. Is machining time of NiTi SMA higher than Ti?

### **Assumptions**

1. SMAs and Titanium alloys are considered difficult-to-machine materials using the conventional machining processes due to their high ductility, work-hardening characteristics and pseudo elastic behavior.
2. Ti and NiTi SMA are commonly used biomaterials

### **Limitations**

1. Laboratory environment: There are different components in the air for example, Oxygen and Hydrogen that might affect the machined surface. Thus, the working environment was controlled in order to have better surface finish and fewer amounts of other elements on the surface.
2. Time: NiTi SMA and Ti-6Al-4V alloy are strong and difficult-to-cut materials to and this property typically prevents machining at high speeds.

Therefore, machining with these materials should be performed with a lower speed for higher accuracy, which might take more time.

### **Definition of Terms**

1. Biocompatibility: Especially of materials used in surgical implants that are not harmful to living tissue (The Free Dictionary, 2015).
2. Cytotoxicity: It is the quality of being toxic to cell (The Free Dictionary, 2015).
3. EDM: Electro Discharge Machining
4. EDS: Energy Dispersive X-ray Spectroscopy
5. SEM: Scanning Electron Microscope
6. XRD: X-ray Diffraction
7. SMA: Shape Memory Alloy
8. MRR: Material Removal Rate
9. TWR: Tool Wear Rate
10. SR: Surface Roughness
11. HAZ: Heat Affected Zone: Portion of the base metal that has not been melted, but whose mechanical properties or microstructure has been altered by the heat of welding or cutting (IADC Lexicon, 2013).
12. Hydroxyapatite: An inorganic calcium-containing constituent of bone matrix and teeth, imparting rigidity to these structures (The Free Dictionary, 2015).
13. Micro-EDM: Micro Electro Discharge Machining
14. Osseointegration: The formation of a direct interface between an orthopedic or dental implant and bone, without intervening soft tissue (The Free Dictionary, 2015).

## **Review of Literature**

### **Background**

A few decades ago, product manufacturers had difficulties cutting several materials due to various features such as high strength, hardness and resistance to erosion (Jahan, Rahman & Wong, 2011). Accordingly, manufacturers require supplementary help aside of conventional machining (i.e., pendulum grinding, turning and milling, etc.) in order to cut advanced material. These types of hard-to-cut materials (Titanium, Nickel, etc.) require special machines with high accuracy and an appropriate surface quality. These characteristics of the hard-to-cut materials cause an increase in the price of machining tools (Pandey, 2010).

A study conducted by Saxena, Kumar and Shukla in 2014, indicated that conventional machining is not acceptable in industries, because the MRR and depth of cut are low. For example, using boron nitride tools in conventional machining produces a cutting depth of 0.1 – 0.5 mm, cutting speed of 20 -30 m/min and feed rate of 0.2 – 0.25 mm/rev. This indicates poor performance of the machining tool (Jahan, Rahman & Wong, 2011).

Considering the high cost of the machining discs and the limited success of their performance, a new non-conventional machining called Electrical Discharge Machining (EDM), was innovated in 1770 by Joseph Priestly. This process removes materials from the workpiece by the electro erosion phenomenon (Li, Bai & Gianchandani, 2013). The principle of EDM is based on thermoelectric energy that occurs between the workpiece and electrode (Saxena, Kumar & Shukla, 2014). The recent generation of EDM, micro electro discharge machining (micro-EDM), is one of the non-conventional machining

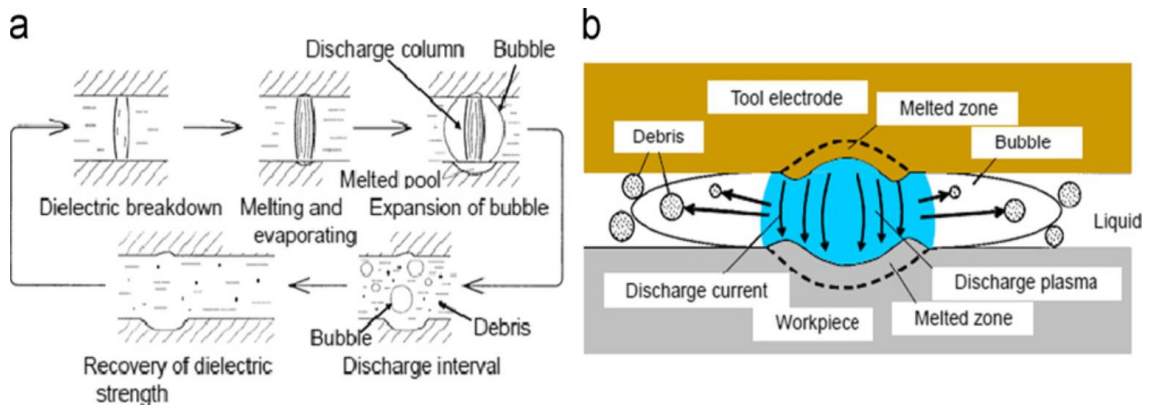
method in the manufacturing field that produces products with complex geometrical profiles with high accuracy (Cheng, Wang, Nakamoto & Yamazaki, 2009).

During World War II, the Soviet government employed engineers to explore one of the critical issues with regard to automotive engines. The government asked engineers to find methods of preventing the erosion of tungsten electrical contacts due to sparking. Lazarenko and Lazarenko, two scientists from Moscow, attempted to control the electrical contact sparking by using oil liquid for electrode. They found that electrodes have constant and predictable sparking in oil rather than in air (Pandey, 2010; Singh, Maheshwari & Pandey, 2004). The invention was a starting point for EDM application in hard-to-cut materials such as Titanium, Tungsten etc. (Pandey, 2010).

### **Micro-EDM Principle**

During the micro-EDM process, discharge occurs between the electrode and workpiece, which causes electrodes to reach the melting phase and evaporate. Since the metal removal of each discharge is very insignificant, it requires high frequencies between  $10^3$  and  $10^6$  Hz to increase its efficiency. The sparking, upon which the removal of material in EDM is based, occurs between the electrode and the work piece. According to Figure 2, with a single spark in the erosion process, positive direct current (DC) reaches the electrode and develops an intense electrical field in the gap. Microscopic contaminants suspended in the dielectric fluid are attracted by the field and are concentrated on the field's strongest point. These contaminants build a high conductivity bridge across the gap. As the field voltage increases, the material in the conductive bridge heats up. Some pieces ionize from the spark channel between the electrode and work piece. At this point, both the temperature and pressure in the channel increase rapidly,

generating a spark. A small amount of material melts and evaporates from the electrode and workpiece at the point of contact. A bubble composed of gaseous by-products of vaporization rapidly expands outward from the spark channel. Once the pole sends the spark, heating action stops, and the spark channel collapses. Dielectric fluid then rushes into the gap, flashing molten material from both surfaces. Thus, EDM residue consists of small, solidified balls of material and gas bubbles (Garg et al., 2010; Liu, Lauwers & Reynaerts, 2010; Nguyen, Rahman & Wong, 2012; Saxena, Kumar & Shukla, 2014; Singh, Kumar & Kuma, 2014).



*Figure 2.* Representation of sparking and gap phenomena in EDM: (a) model of EDM gap phenomena and (b) discharge phenomena in EDM gap (Jahan, Rahman & Wong, 2011).

The finished workpiece of EDM has three different layers. The first and top layer called the surface layer has small globules of removed workpiece metal particles and easily can be removed. The layer below is the recast layer where the EDM changes the metallurgical structure of the work-piece. The final layer is called the heat effected zone (HAZ), which is exposed to heat, but not melted. The EDM is able to melt the workpiece with a high degree of precision compared to other conventional machining (Akbari, Chegini, Rajabnejad & Ave, 2009).

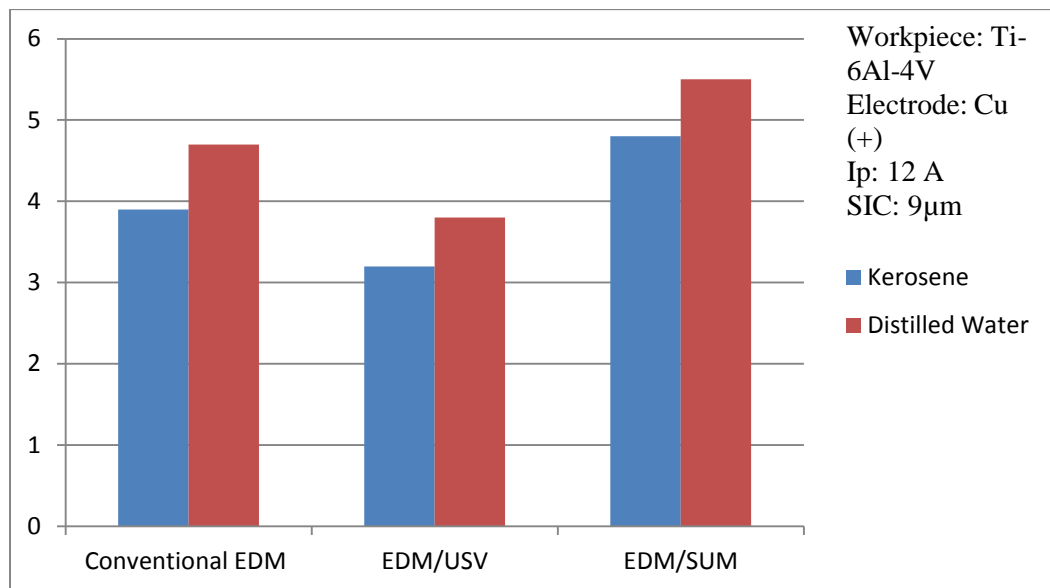
It is important to have the distance between the previous discharge location far from the next discharge location. At the end of each discharge duration, the surface temperature of the electrode and the workpiece decrease leading to the recombination of ions and electrons as well as recovery of dielectric strength breakdown. However, when the remaining materials on the surface cool down and change to spherical components in the dielectric liquid, it causes weakening of dielectric strength of the liquid. Hence, there should be a distance between the previous and the next discharge pulse so the debris particles can be removed easily to improve dielectric strength (Saxena, Kumar & Shukla, 2014).

There are different kinds of dielectrics with different densities, chemical compositions, and cooling rates. These different kinds of dielectric fluids have varying impacts on micro-EDM characteristics. Thus, dielectric liquid plays an important role in the EDM process. Kerosene and dielectric water are used to remove materials in EDM as dielectric liquids (Fonda, Wang, Yamazaki & Akutsu, 2007; Kibria & Bhattacharyya, 2010).

When kerosene is used for an extended period of time in machining, its dielectric properties decline. Moreover, at high temperatures, kerosene loses its strength and breaks down into CO and CH<sub>4</sub> due to high discharge energy, leading to pollution of the air around the EDM. Due to the industrial safety concerns and lack of sustainability with the use of kerosene, distilled water is replaced in industrials as a new dielectric liquid (Kibria, Sarkar, Pradhan & Bhattacharyya, 2010).

Distilled water is being used as a substitute for hydrocarbon oils (kerosene) because it does not release any harmful gases, has a better material removal rate, and has

a better tool wear rate. Even though deionized water provides a safe working environment, it reduces the machining accuracy (Lin, Lin & Ko, 2002). So, investigators have conducted various studies using powder-mixed dielectric fluids composed of different sizes of powder particles and their impact on EDM performance (Kibria et al., 2010; Tang & Du, 2014). Figure 3 shows a better performance for distilled water as compared to kerosene in the surface roughness of EDM process in different machining processes.



*Figure 3.* Comparison of surface roughness for different machining processes (adapted from Kumar, Singh, Batish & T. Singh, 2012).

One other significant factor in the EDM process that affects machining performance is the amount of energy supplied to a work piece (Shen et al., 2014). The total energy distribution percentage for different tools depends on the electrode wear ratio, surface roughness, and material removal rate. Moreover, the energy that is supplied to the EDM is mostly converted to heat, light and sound. During this process, most of the

heat energy is allocated to the work piece, dielectric and tool electrode, while the supplied light energy is consumed by radiation and ionization (Shen et al., 2014).

The energy distribution ratio is measured by comparing the measured temperature of the electrode with the calculated consequences obtained under the assumed ratio of the energy distributed into the electrodes (Singh, N. Kumar & A. Kumar, 2014). For this purpose, the first temperature rise of electrodes should be considered and is typically performed by a thermocouple that is placed in an appropriate location near the discharge location. The temperature rise in the electrode can be calculated using a thermal conduction model, by assuming an energy distribution ratio. The calculative method is repeated until the measured results of the temperature rise matches that of the calculation with an assumed ratio of the energy lost to the electrode through conduction to the total energy discharge. For example, Shen and his coworkers considered the amount of energy distributed into an electrode ( $E_e$ ) and workpiece ( $E_w$ ) from the total energy distributed during the EDM process. According to Figure 4,  $E_d$  shows the amount of energy absorbed by dielectric liquid that comes from the increase in temperature and liquid movement. Also,  $E_r$  indicates the amount of energy lost to light, sound and ionization. The relationship between these energy distributions of  $E_e$ ,  $E_w$ ,  $E_d$ , and  $E_r$  are calculated using the relation  $E_e + E_w + E_d + E_r = 100\%$  (Shen et al., 2014).



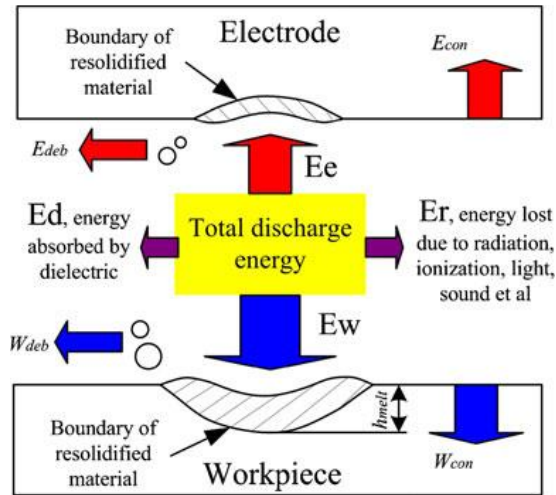
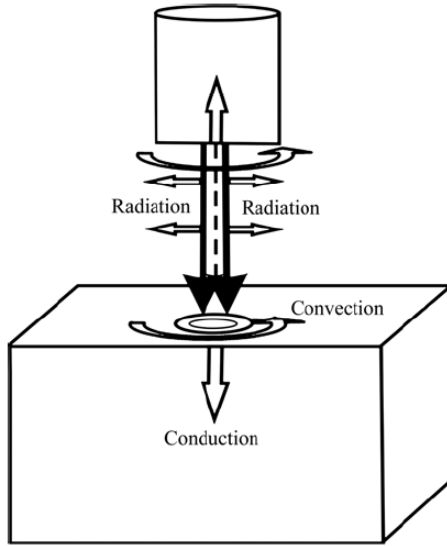


Figure 4. Energy distributed in EDM process (Shen et al., 2014)

### Thermal Model of EDM Process

The overall EDM process includes simultaneous interaction of thermal, mechanical, chemical and electromagnetic phenomena. For example, the thermal energy component involves the heat transferred in the process due to conduction and convection. Hence, the EDM process can be explained as a thermal process. Material temperature will go up by the action of high-energy electric spark melting and vaporizing a small area on the electrode surface. Small amounts of molten material are removed from the surface at the end of the pulse on-time. Figure 5 shows the heat transfer in the EDM process (Xie, Wang, Wang & Zhao, 2011).



*Figure 5. Thermal Model of EDM process (Xie et al., 2011).*

### **Electric Discharge Machining of Ti–6Al–4V**

One of the difficult-to-cut materials is Titanium (Ti), which is used in various applications in aircraft and biomedical industries because of its chemical and mechanical properties (Hascalik & Caydas, 2007). Because of the high thermal conductivity and high strength of the titanium, EDM is an appropriate process for cutting this alloy for making high quality products. According to Fonda et al. (2007) and Nguyen, Rahman and Wong (2012), the properties of Ti–6Al–4V workpiece require more energy to conduct electrical power. The energy absorbed by the workpiece causes a temperature rise due to conduction and an eventual dissipation with time. Titanium is a lightweight metal with a higher density. Comparing it with other metals, such as Iron, Ti has a higher melting point (Ti melting point is 1,668°C and iron is 1,560°C) and lower modulus of elasticity (Ti is around  $110 \times 10^9$  Pa and steel is  $210 \times 10^9$  Pa) (Kibria et al., 2010; Kumar et al., 2012). Also, Ti can be cold rolled to 90% reduction in thickness at room temperatures without cracking.

Titanium alloys can be divided into three groups: alpha, alpha-beta, and beta. The alpha group cannot be used in aircraft applications and is also not appropriate for heat treatment. Aluminum and tin are the most common alloys in the alpha group. The second group, alpha-beta, is harder than the first group because they are strengthened with heat treatment and suitable for applications such as aircraft turbines, marine hardware, and chemical processing equipment. The hardened titanium alloys are in the third group, which are denser than other types of titanium alloy (densities ranging from 4,800 to 5,050 kg/m<sup>3</sup>) (Kumar et al., 2012). However, beta alloys, though the smallest group, are used in broader and more important aircraft parts.

Temperature is one of the important factors that affect materials' electrical conductivity. During the EDM process, the amount of heat that is supplied for each discharge spark is higher than the melting temperature of every material ( $\sim 3000^\circ\text{C}$ ) (Fonda et al., 2007). Materials can quickly absorb the heat because of the low electrical resistance, so EDM can remove heavy materials from the work piece (Newton, Melkote, Watkins, Trejo & Reister, 2009; Nguyen, Rahman & Wong, 2010; Shen et al., 2014).

The Ti-6Al-4V properties of low thermal conductivity and high electrical resistivity make it difficult for the workpiece to conduct the amount of electrical energy that is used for the EDM (Zhang, Reddy & Deevi, 2001; Shen et al., 2014). Indeed, once the energy is absorbed by the workpiece, it is difficult to dissipate the heat without causing a steady increase of workpiece temperature. Therefore, when the electrical resistivity and thermal conductivity are increased, the temperature also increases (see Figure 6) (Fonda et al., 2007).

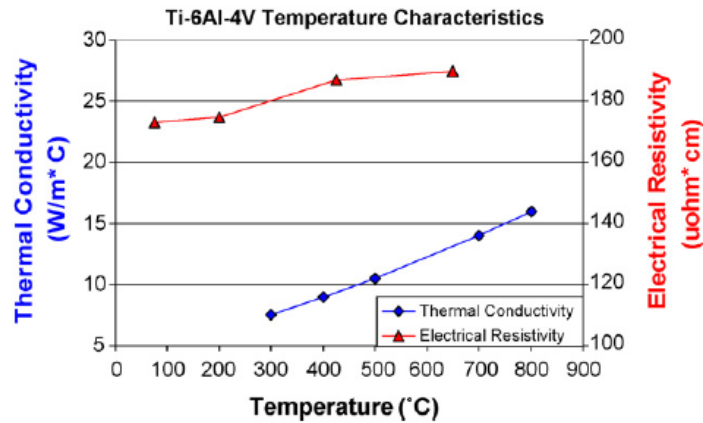


Figure 6. Electrical resistivity and thermal conductivity vs. temperature for Ti–6Al–4V (Fonda et al., 2007).

Recently, researchers have attempted to explore the effect of EDM parameters on the surface of Ti-6Al-4V alloy using different electrode tools (Kao, Tsao, Wang & Hsu, 2010). In order to optimize EDM’s process parameters, researchers developed a “hybrid model using artificial neural networks and genetic algorithm” (Kao et al., 2010, p 395). This model helped to optimize the Surface Roughness (SR) in the EDM process through the simultaneous effect of peak current and voltage for Ti-6Al-4V (Nguyen, Rahman & Wong, 2010).

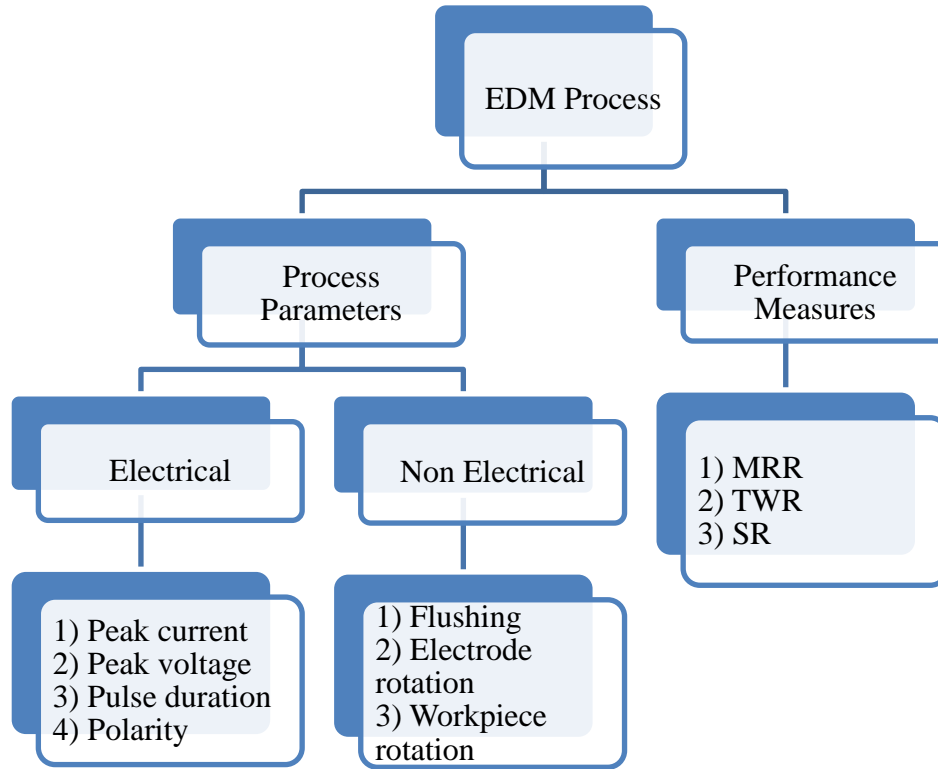
### Process Parameters and Performance Measures of EDM

One of the challenging problems that constrain expanding application of the EDM technology is improving the surface quality of the workpiece. When advanced materials appear in the field, it is not possible to use existing models and hence, experimental investigations are always required. The essential performance characteristics in the EDM process include Material Removal Rate (MRR), Tool Wear Rate (TWR) and Surface Roughness (SR). It is difficult to obtain the exact quantification of these parameters because there are several uncertain factors and situations. The optimal selection of

process parameters is essential for the process of increasing production cost as it significantly reduces machining time (Ayesta et al., 2013).

The process parameters in the EDM are divided in two branches: electrical and non-electrical parameters. The EDM process is of a stochastic thermal nature having a complicated discharge mechanism. Therefore, it is difficult to explain all the effects of these parameters on performance measures (Ojha, Garg & Singh, 2010, p.712).

Researchers attempted to optimize the parameters through recognizing the effects on operating variables. Peak voltage, peak current, pulse duration, electrode gap and polarity were categorized under the electrical part (see Figure 7) (Ojha, Garg & Singh, 2010, Srivastava & Pandey, 2012).



*Figure 7.* Process parameters and performance measures of EDM Process (Ojha et al., 2010).

### **Influence of Process Parameters on Performance Measures of EDM**

Peak current: Peak current is one of the most important parameters in the EDM process, and it is measured in amperes. A higher value of peak current is required in rough machining operations and in cavities or details with large surface areas (Kumar et al., 2012). However, even though higher current increases the material removal rate (MRR), it reduces the precision of machining due to excessive wear (Kumar et al., 2012; Saxena, Kumar & Shukla, 2014). A higher amount of current also requires new tool materials because of excessive tool wear during machining (Kumar et al., 2012; Tang & Du, 2014).

Peak voltage: The discharge voltage in EDM is related to the spark gap and breakdown strength of the dielectric (Kumar et al., 2012). The open gap voltage will be increased until it creates ionization by the dielectric before the current is flowing (Saxena, Kumar & Shukla, 2014). When the current starts to flow, the voltage is dropped and used at the working gap level. The amount of voltage determines the width of the spark gap before work is begun and is fixed based on the leading edge of the electrode and work piece (Kumar et al., 2012; Tiwary, Pradhan & Bhattacharyya, 2013). By increasing voltage, the surface roughness, MRR and TWR will be increased because electric field strength rises. The gap steadily increases and improves the flushing conditions by higher voltage (Kumar et al., 2012).

Pulse duration: (Pulse on-time and pulse off-time): In the EDM process, each cycle has pulse on-time (pulse duration), and pulse off-time (pause interval) which is expressed in microseconds ( $\mu$ s). The machining is performed during on-time, while the removed materials are flushed away from the machining zone during off-time (Kumar et al., 2012, p.93). Pulse on-time has an influence on machining. For example, when pulse on-time is increased, machining makes a broader, deeper and faster crater, which creates poor surface and higher MRR (Kumar et al., 2012; Tiwary, Pradhan & Bhattacharyya, 2013). The pulse off-time is the period that deionization of the dielectric takes place (Kumar et al., 2012). In other words, it is the duration between sparks in the process, which change the molten materials to solidify and finally wash out from the work piece. The off-time controls the speed and stability of the cut. The spark will be unstable if the pulse off-time is short. In addition, if the off-time is insufficient, it can slow down the

cycle or make the cycling erratic. Thus, these two parameters have direct influence on the precision, as well as on MRR and SR.

On the other hand, the major non-electrical parameters are flushing of dielectric, workpiece rotation, and electrode rotation (Ojha, Garg & Singh, 2010). These non-electrical parameters can have positive effects on performance measures. For example, workpiece rotation can improve the dielectric fluid movement in the spark gap as well as optimize temperature dispensation across the work piece. This process creates a better performance of MRR and TWR (Ojha et al., 2010, Srivastava & Pandey, 2012, Raghuraman, Thirupathi, Panneerselvam & Santosh, 2013).

In 2012, Daneshmand, Farahmand, Lotfi and Mortazavi studied the effect of the input parameters of the EDM process, such as voltage, discharge current, pulse on time and pulse off time on the output parameters for EDM of SMA. Researchers during this investigation employed brass tools, de-ionized water and Taguchi's method of the design of experiments for optimizing the machining performance. According to the result, the pulse energy increased with the discharge current and voltage increased and as a result, the MRR and TWR increased. The TWR increased in a specific range of pulse on time from 35 to 50 $\mu$ s, but the TWR decreased when pulse on time goes up from 50 to 100 $\mu$ s. Also, the MRR increased with pulse on time increased. It was also found that by increasing pulse off time, the MRR and TWR was increased. They reported that the MRR has an indirect relation with relative electrode wear. When the voltage increased, relative electrode wear increased and as a result, the MRR decreased. The MRR increased with reduction of relative electrode wear because the discharge current and pulse on time went up (Sabouni & Daneshmand, 2012).



The research result from Daneshmand et al., (2013) indicated that with an increase in EDM parameters such as voltage and discharge current, the amount of TWR and SR consequently increased. However, The TWR gradually went up with an increase in pulse-on time until reaching a certain point, then decreased. But, the MRR, SR and TWR were decreased with the increase of pulse-off time.

### **NiTi Shape Memory Alloys**

Nickel – Titanium (NiTi) alloys are the most important class of shape memory alloys and inter-metal binary combinations (Alidoosti et al., 2013). NiTi alloys are very popular in industries due to properties such as superelasticity, adaptive responses, memorized capability, high damping characteristics, stress hysteresis and magnetic resonance imaging (MRI) compatibility (Stoeckel, Pelton & Duerig, 2004; Chen, Hsieh, H. Lin, M. Lin & Huang, 2008; Alidoosti et al., 2013). One of the important characteristics of SMAs is the strain increase of nearly 8% heating above austenite finish temperature  $A_f$  or unloading in a polycrystalline state. These kinds of properties of NiTi alloys have resulted in many applications in the medical, aerospace and robotics, military, automotive, and biomedical industries.

Buehler and his colleague at the U.S. Naval Ordnance Laboratory took the primary steps towards the discovery of shape memory alloys in 1960. They discovered the shape memory effect in an equiatomic (containing the same amount of two or more atoms) alloy of nickel and titanium, which helped them be successful in the field of shape memory materials. They named the alloy they discovered as Nitinol (Nickel-Titanium) (Alidoosti et al., 2013).

SMA's produce high actuation strains (~6-10%), stresses (~100-400 MPa) and work output (~10 MJ/m<sup>3</sup>) as a result of reversible martensitic phase transformations (Kaynak, Karaca & Jawahir, 2011). Some of the mechanical attributes of NiTi are summarized in Table 1.

Table 1

*The mechanical properties of NiTi*

	Austenite	Martensite
Young's Modulus	30-83 GPa	20-45 GPa
Ultimate Tensile Strength	800-1900 MPa	800-1900 MPa
Recoverable Strain	8-10 %	8-10 %
Poisson Ratio	0.33	0.33

(Falvo, 2008)

NiTi shape memory alloys have two totally different phases (temperature-dependent crystal structures): martensite (lower temperature) and austenite (higher temperature or parent phase). The fundamental reason of NiTi's super elasticity and memorability is a reversible martensite transformation in the solid phase (see Figure 8).

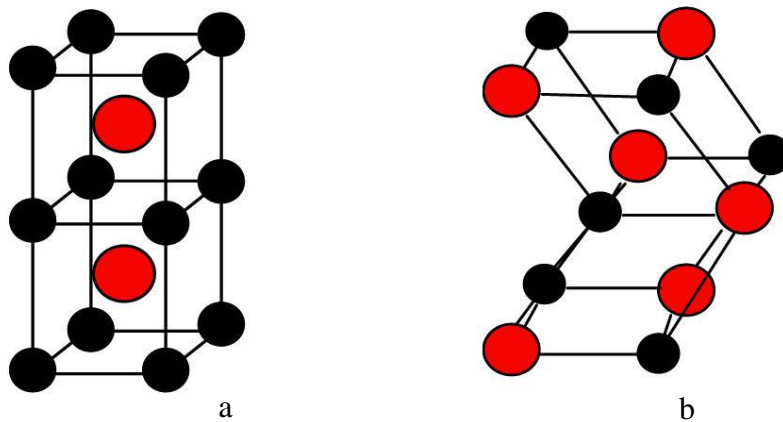
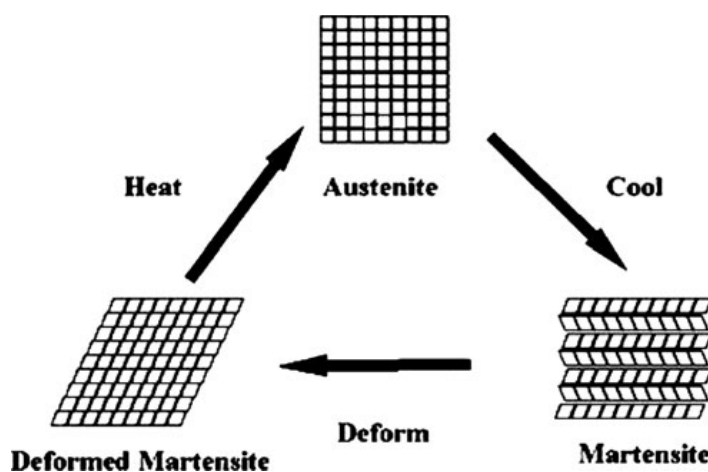


Figure 8. (a) Austenite and (b) Martensite structure (Falvo, 2008).

Shape Memory Alloys are known as a smart metal with the capability of changing the shape by changing heat and the temperature. For example, when SMA deforms through heating, it can regain its original shape. “Deformation temperature is the phase transformation temperature of austenite to martensite and vice versa (Daneshmand et al., 2013, p. 7485).” Properties such as Young’s modulus, electrical resistance and damping behavior are remarkably different for the two phase transformations of NiTi (LotfiNeyestanak & Daneshmand, 2013). NiTi-SMA gets their unique physical properties from the rare behavior of Nitinol in phase transformation, which is contingent on the temperature of austenite and martensite in atomic scale. Nitinol remains in the austenite phase in relatively higher temperatures and in martensite phase in relatively lower temperatures. This distinct behavior in transformation between the two phases means that a product made of NiTi-SMA transforms to its martensitic phase when cooled below the transformation temperature, which allows for easy deformation of the product (see Figure 9).



*Figure 9. The shape-memory effect of NiTi SMA (Li, Zeng & Tang, 2010)*

To reach the final form, a special heat treatment, similar in both super elastic and shape memory to properties of Nitinol, will be done while maintaining the parameters such as temperature and timing efficiency in order to coordinate the shape and piece properties. Afterwards the product is cooled through various methods, preferably by quenching in water or fast cooling in air. There are two common shape memory effects; these are the one-way and two-way shape memory effects. As the names suggest, the difference between the two is that the one-way has only one original form, while the two-way effect allows the sample to remember two different original forms (Li, Zeng & Tang, 2010)

For the one-way shape memory effect, or, simply, shape memory effect, shape recovery is achieved only during heating. By the stress-free cooling of austenite, a complex arrangement of different martensite is created. Between the martensite variants and twinning, when an average of microscopic transformation strain is zero, the self-accommodation increase occurs. The movement of twinned to de-twinned martensite causes to achieve lower stress levels than plastic yield with longer inelastic strain. These strains are recovered by the reverse transformation that is induced by heating, and since the stress has now reoriented the martensite variants, reversion to austenite creates another large transformation strain (Figure 10) (Falvo, 2008).

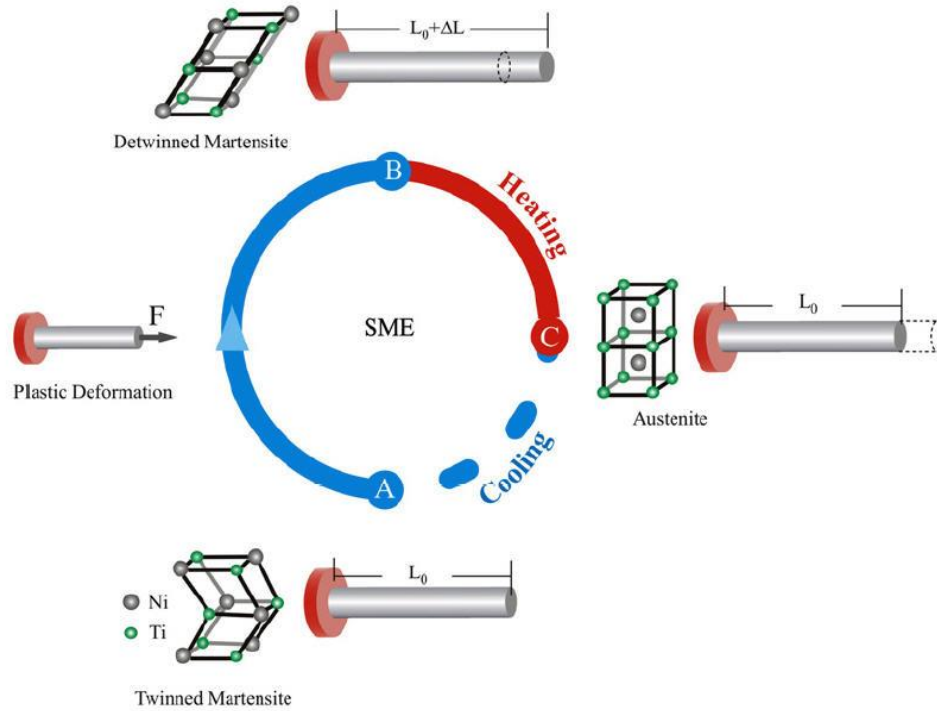
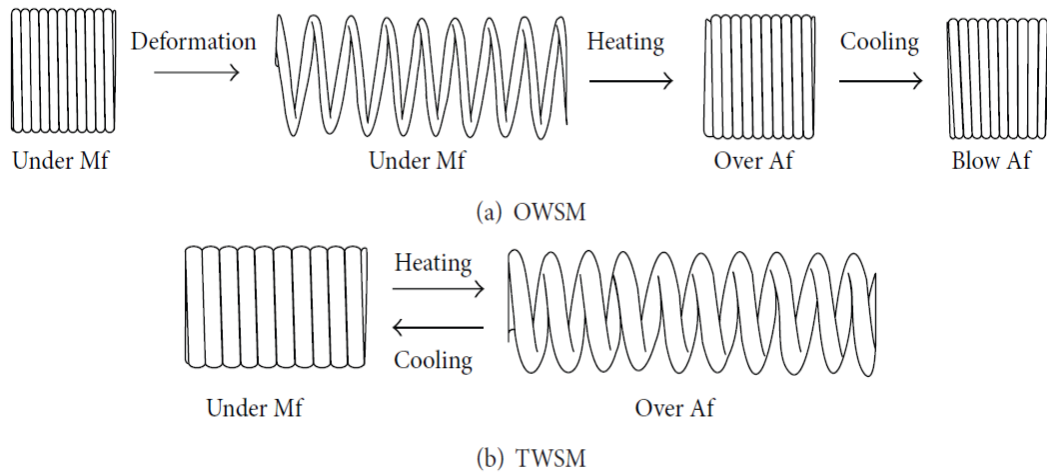


Figure 10. Shape memory effect phenomenon in shape memory alloys (Falvo, 2008).

This strain will have the same amplitude, but in opposite direction to the inelastic strain. This will return the SMA to its original shape of the austenitic phase. Multiple self-accommodated martensite can be affected significantly by cooling with no remarkable change in shape. With this shape memory method, the sample is cooled below the  $M_f$  (Martensite finish) temperature to form properly first, and then heated above the  $A_f$  (Austenite finish) temperature until it gets its austenitic shape. The method is then repeated 20 to 30 times for the procedure to be completed. The sample will finally obtain its planned shape below  $M_f$  temperature and any other shape above the  $A_f$  temperature. In the two-way shape memory effect, the shape of sample is changed above the  $M_s$  (Martensite start) temperature by stress then cooled up to under the  $M_f$  temperature (Figure 11) (Falvo, 2008; Elahinia, Hashemi, Tabesh & Bhaduri, 2012;

LotfiNeyestanak & Daneshmand, 2013).



*Figure 11.* Two instructions of two-way memory training (LotfiNeyestanak & Daneshmand, 2013).

### **Electrical Discharge Machining of NiTi SMA**

In order to extend the applications of NiTi, certain machining technologies have been developed for manufacturing products with high accuracy and complicated shapes. Without proper techniques, certain difficulties are associated with the machining NiTi alloys in industries. With the use of special equipment, tools, and highly experienced operators, the machining of NiTi becomes rather expensive. Conventional machining techniques such as milling and drilling can have significant influence on the behavior of the SMA materials due to their high thermal and mechanical effects. This sometimes leaves the material, especially parts with low dimensions, with excessive degradation in performance. Consequently, certain non-conventional processes have been undertaken to fabricate NiTi components (Chegini & Akbari, 2012; LotfiNeyestanak & Daneshmand, 2013).

The most preferred of these processes is laser machining due to its high speed, accuracy, and the capability for rapid prototyping. However, this method has disadvantages such as the extension of HAZ and micro-cracks. Another method is electro-discharge machining (EDM), which works well with most Nitinol compositions, assuring minimal influence on the material due to the intrinsic characteristics of this technique. EDM has a great advantage since it has no contact to the work piece. This kind of machining acts independently of the hardness and toughness of the material having no effect on the power. In some applications; however, there might be a need for removing the recast surface layer that is formed on the material in the machining zone. This is due to the oxides and contaminants that could have been created from the electrodes and dissolved dielectric mediums depending on the application. Furthermore, during the EDM process, high temperatures can cause melting at the surface that can ultimately have negative effects on HAZ (Akbari et al., 2009).

Lin, Lin & Cheng, (2001) reported that the electro-discharge energy mode including the pulse current and pulse duration significantly influence the materials removal rate of TiNi SMAs in the EDM process. These authors suggested that for an accurate EDM machining of SMAs, longer pulse duration and a lower pulse current should be selected. There are recast layers or electro-discharge craters on the SMAs surface after EDM that involve oxides ( $\text{TiO}_2$ ,  $\text{TiNiO}_3$ ) and the other deposition particles from the electrode. The recast layer thickness was found to increase with increasing pulse duration (Lin, Lin & Cheng, 2001).

### **Concluding Remarks on Literature Review**

It can be seen from the literature review that although there are various studies (Fonda et al. 2007, Akbari et al., 2009 and Daneshmand et al., 2013) on the EDM of Ti-6Al-4V and NiTi materials, most of those studies are on the conventional EDM. Very few studies have been conducted on the micro-EDM of these two materials. In addition, there is no comparative study on the performance of two materials. Moreover, the surface generated from the EDM and micro-EDM of these two materials is very important because of their extensive applications in biomedical industries.



## **Methodology**

### **Experimental Procedure Design**

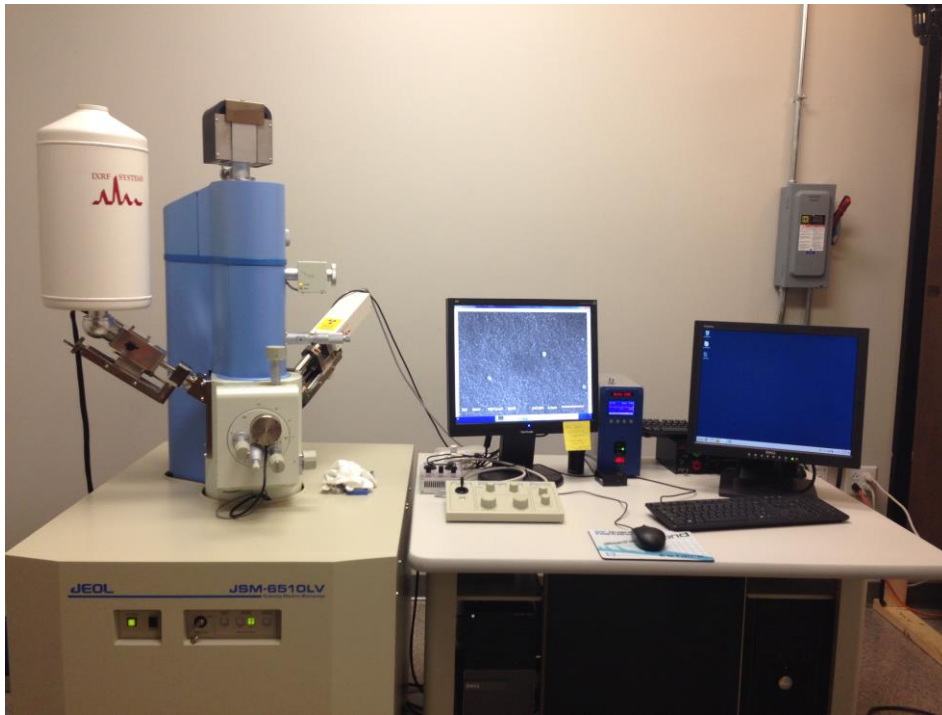
The essential performance characteristics in the EDM process contain material removal rate (MRR), tool wear rate and surface roughness (SR). It is difficult to obtain the exact quantification of these parameters because there are several uncertain factors and various situations. In this study, to investigate the surface modification on Ti-6Al-4V and NiTi SMA, micro-features were fabricated on the NiTi SMA and Ti workpieces using the micro-EDM process at different parameters. The operating parameters were gap voltage, capacitance and electrode rotation speed. In addition to surface characteristics, the machining time was also recorded and compared for two materials.

During the micro-EDM process, the material was removed by the electric sparks at very high temperature. Therefore, it was expected that the high temperature generated during the machining process may affect the surface during the process. However, the most important thing that this study aims to investigate was whether the surface modification that occurred during the process affect the future usefulness of the product. Therefore, different characterization techniques were used to evaluate the biocompatibility of the micro-EDM generated surface.

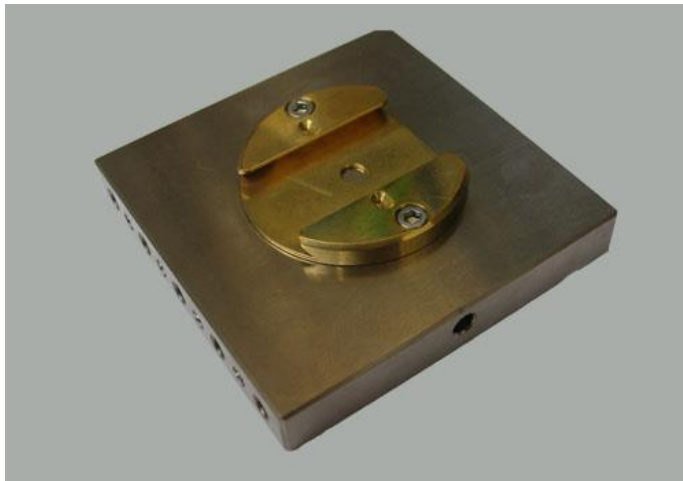
This research used three different materials characterization techniques: such as 1) Energy-Dispersive X-ray spectroscopy (EDX) analysis, 2) X-ray Diffraction (XRD) and 3) Scanning Electron Microscope (SEM). Scanning electron microscope (SEM) is a method for high-resolution imaging of surfaces in both bright and dark field modes. The SEM images of the machined surface showed the variation of crater sizes with different parameter settings, as well as the presence of surface defects, such as porosity, micro

cracks and inclusions. The EDX analysis allowed finding the percentage of different materials on the machined surface. From the EDX analysis, the researcher tried to find any harmful substances on the machined surface that are not biocompatible. The XRD analysis could find the formation of different compounds on the machined surface after the micro-EDM process.

After machining, the researcher took pictures from both workpieces by SEM in higher and lower magnification. Higher magnification helped to analyze the whole surface of materials. Lower magnification helped analyze craters, recast, and re-solidification materials. The SEM and EDX were in the Biology Department at Western Kentucky University (Figure 12). The sample was mounted on an SEM holder (Figure 13). The sample then is placed in the chamber and connected to the sample by a long rod. The basic principle of SEM is colliding electrons with atoms in the sample. Electrons enter the sample from the column that is linked to the chamber. Electrons pass through the sample and are detected by diode detectors. EDX analysis was combined with SEM, which produces the X-ray spectrum on the sample from the entire scan area of the ESM. EDX analysis shows the characteristics of the present elements on the workpiece on an area as small as a nanometer in diameter (Hanfer, 2006). Each element has a unique atomic structure so it is possible to show this with a series of peaks in the X-ray spectrum. This method measures the number and energy of the emitted X-rays from the sample.



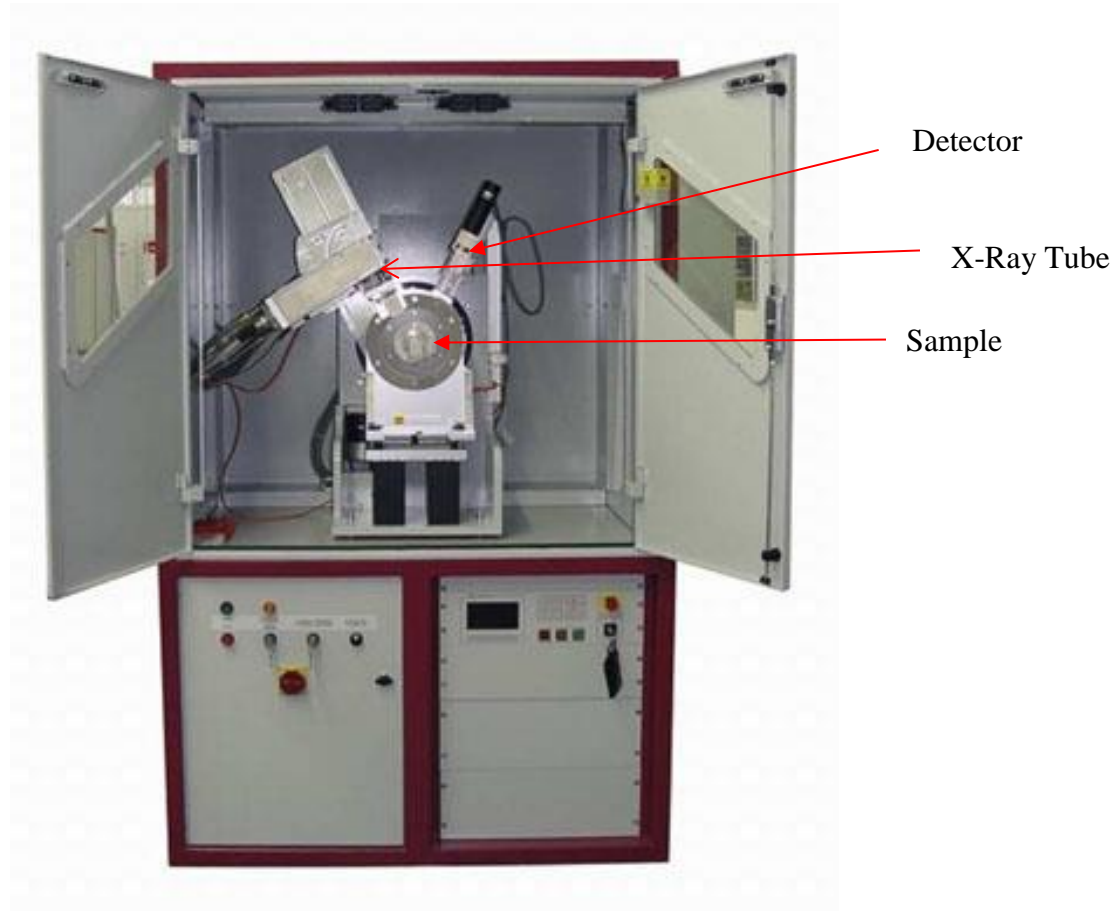
*Figure 12. SEM set up*



*Figure 13. SEM holder*

XRD provides the characterization of crystalline materials and the definition of their structure. The XRD machine was located at the Center for Research and Development (CRD) at WKU. XRD generates X-rays by bombarding a sample with a beam of electrons released from a hot filament (Figure 14). The first step in XRD

analysis is putting a sample into the holder and closing the door. Before running a machine, parameters such as the detector situation and X-ray, the amount of energy and machining time are defined by a computer which was connected to the machine.



*Figure 14. XRD machine*

## **Materials**

The base materials that were used in this study are commercial Ti-6Al-4V and NiTi SMA. The chemical composition of Ti-6Al-4V is given in Table 2 and the list of mechanical properties of studied material is provided in Table 3. Table 4 presents the chemical composition and properties of NiTi SMA. The independent variables that influence the machining time and surface finish are provided in Table 5.

Table 2

*Chemical composition of Ti-6Al-4V alloy (wt%)*

Ti	Al	V	Fe	O	C	N	H
89.464	6.08	4.02	0.22	0.18	0.02	0.01	0.0053

(Hasc,Alik &amp; Aydas, 2007)

Table 3

*Workpiece material properties (Ti-6Al-4V)*

Properties	
Density (Kg/m <sup>3</sup> )	4430
Hardness (HV20)	600
Melting Point	1660
Electrical Resistivity (Ω-cm)	0.000178
Thermal conductivity (watts per meter Kelvin: W/m-K)	6.7

(Hasc,Alik &amp; Aydas, 2007)

Table 4

*Workpiece material composition and properties (Shape Memory Alloy)*

Composition	NiTi: Ni (55.8 %), Ti: 44.2%
Density (Kg/m <sup>3</sup> )	6500
Melting Point (°C)	1310
Electrical Resistivity (Ω-cm)	0.00082
Thermal conductivity (W/m-K)	8.6

(Rasheed, Al-Ahmari, EI-Tamimi &amp; Abidi, 2012)

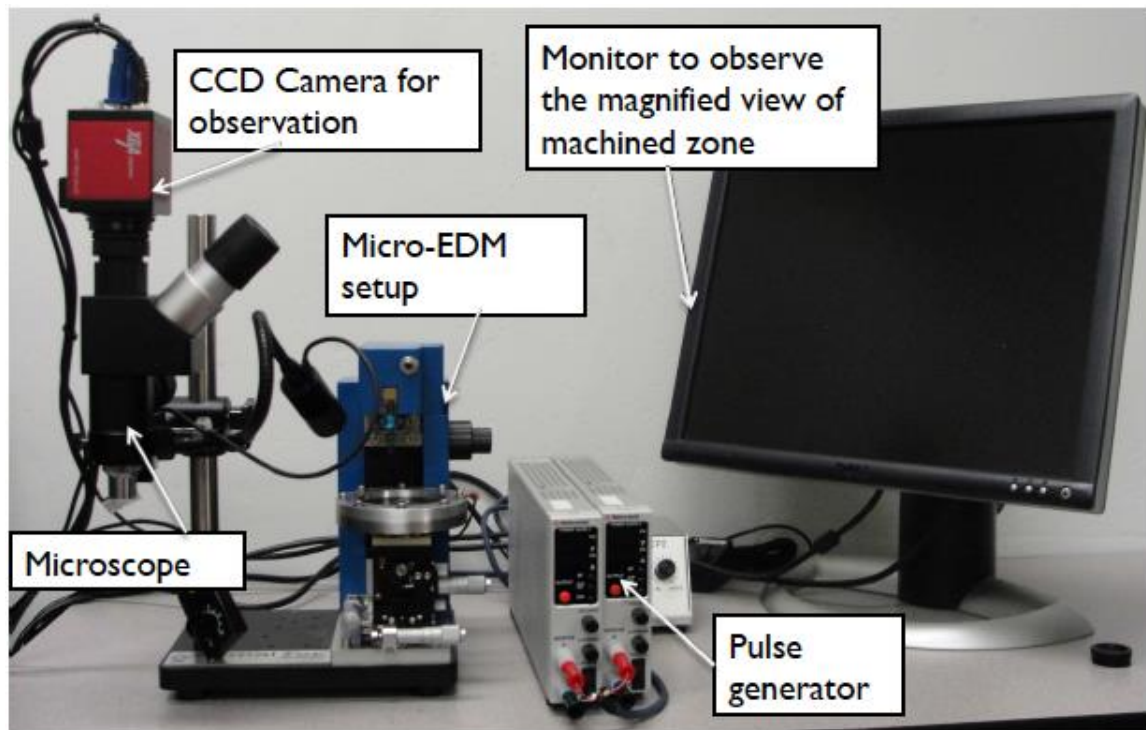
Table 5

*The operating parameters for micro-EDM of Ti-6Al-4V and NiTi*

Machining condition	
Discharge voltage	60
Capacitance (Pf)	1000
Electrode rotational speed (rpm)	3500
Dielectric	De-ionized water

### **Experimental Setup**

In order to perform the electro-discharge machining on NiTi and Ti-6Al-4V workpieces, a desktop micro-EDM machine tool was used. The model of the machine is ED009 from Small Tech. Figure 15 shows the photograph of the micro-EDM setup. The major components of the micro-EDM setup are the machine tool itself, the pulse generator, the Charge-Coupled Device (CCD) camera associated with the monitor for observing the discharging and locating the machining region accurately, and the microscope for in-situ analysis.



*Figure 15.* Micro EDM Set-up

## **Results and Discussion**

Electrical Discharge Machining (EDM) is one of the non-traditional technologies that remove materials from a workpiece through a series of electric sparks that occur between the workpiece and cutting tool with presence of dielectric liquid. The purpose of this research was to analyze and compare the machined surface of NiTi SMA and Ti after micro-EDM, and to identify the optimal parameters for micro-EDM of both materials.

This research had two parts:

1. Comparing and analyzing the surface finish of Ti and NiTi after machining (Research question 1, 2 and 3).
2. Comparing the effect of voltage, capacitance and tool rotational speed based on the machining time on both Ti and NiTi workpieces (Research question 4).

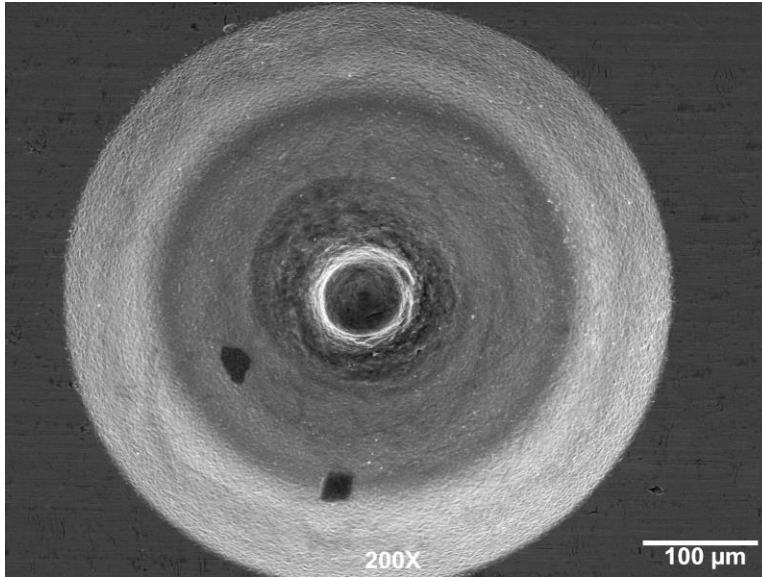
### **Part 1: Surface Analysis of NiTi SMA and Ti after Machining**

One of the most significant factors in the manufacturing and machining process is reaching better surface finish. Jaware and Takale (2015) mentioned that better surface quality and smoother surface of a product can impact the life and cost, cycle time and reliability of the product. In order to compare the surface, the researcher created different patterns on the both Ti and NiTi workpieces. After machining, both workpieces were cleaned with acetone, water and de-ionized water. Workpieces were placed in a small measurement glass that included acetone, then a vibration machine was used to remove remaining materials from the surface. Washing with de-ionized water was done after the vibration machine. The surface quality was observed by SEM method with different magnifications. Higher magnification images were taken to analyze the closer view of surfaces such as craters, debris and resolidified materials.

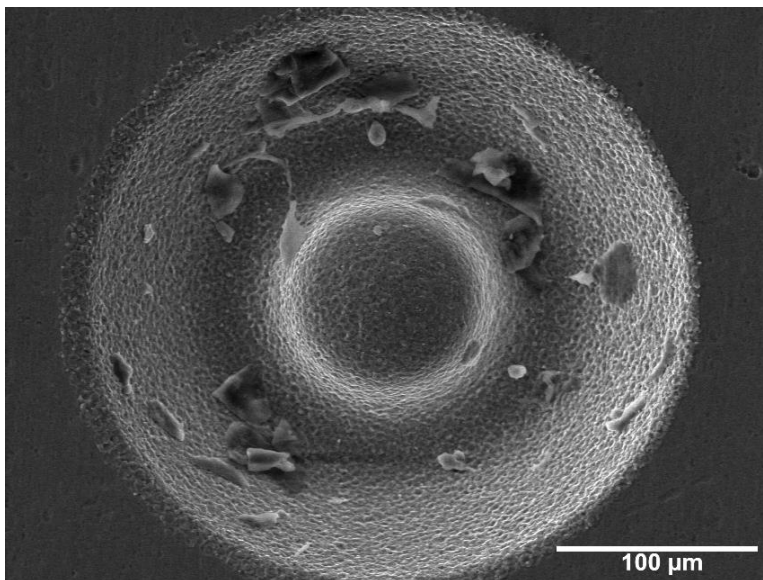


The same parameters and situations including voltage, capacitance, tool speed, EDM oil, and Tungsten tool were used for this investigation. The first experiment was creating a single blind hole on both workpieces that is shown in Figures 16 and 17. The results indicated that the number of particles remaining on the EDMed surface after machining is higher for the Ti workpiece. Based on the SEM pictures, different electrode discharge craters and recast materials were observed from the surface. These craters on the surface can be due to the rapid shrinkage of re-cast materials. The craters occurred when the recast materials became more brittle during the machining and released the shrinkage stress (Alidoosti et al., 2013). The different size of particles debris depends on discharge spark concentration during the machining.

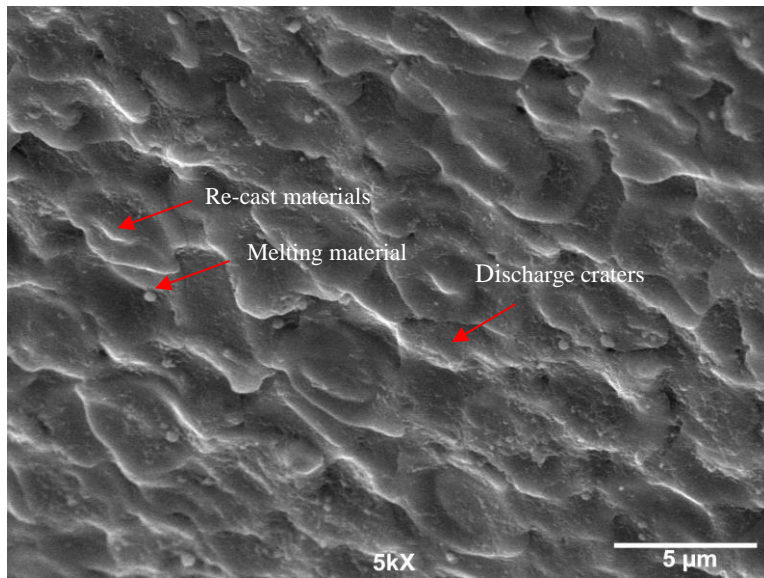
Results also indicated different surface finishes on the centers and edges of the NiTi SMA and Ti workpieces. According to the SEM pictures, the spark concentration on the centers was higher than the edges. Because of the tool wear rate during the machining, the electrode tool became semispherical and tapered towards the center. Higher magnification of SEM helps to understand the machining effect on the workpiece with various degrees of micro-cracks and craters in deeper surfaces. Figures 18 and 19 show discharge craters, melting drops and recast materials on the machined surface at the higher magnification for both workpieces.



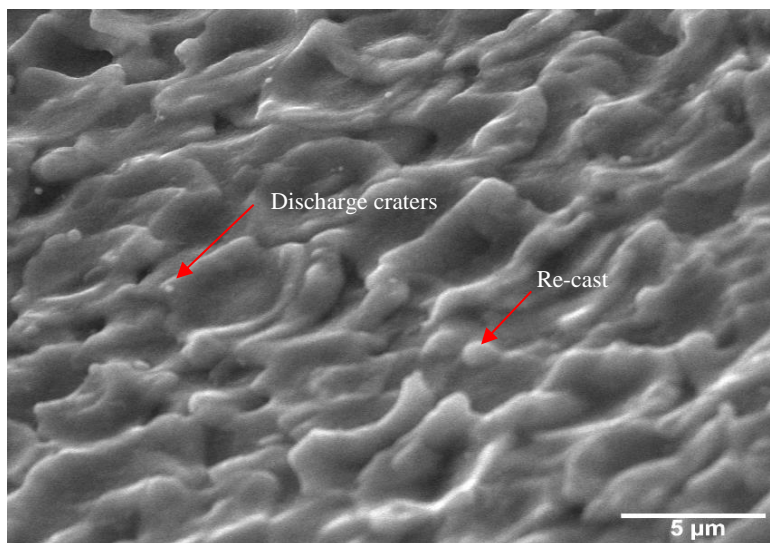
*Figure 16.* Single blind hole of NiTi SMA



*Figure 17.* Single hole of Ti-6Al-4V



*Figure 18.* The SEM micrographs of the NiTi SMA surface (Higher magnification)



*Figure 19.* The SEM micrographs of the Ti surface (Higher magnification)

### **Energy Dispersive X-ray (EDX) Analysis**

This research used dielectric fluid to flush away the melted materials from the workpiece. This dielectric fluid decomposes during the EDM cutting by high temperature or discharge sparks, which is consequently absorbed by the removed materials. EDX analysis shows the compositions of materials before and after micro-EDM of both

workpieces. Before machining on Ti-6Al-4V, a rich amount of Ti was observed on the surface through EDX analysis. On the other hand, after machining there are significant amounts of carbon (C) and oxygen (O) penetration on the Ti workpiece surface. The reason for this is the decomposing of EDM oil into C and O during the electrical discharge machining. Working in the lab environment influenced the machining condition because the oxygen from the environment remained on the surface after machining.

The researcher compared before (1) and after (2) machining of the EDM surface with EDX analysis shown. The data from EDX analysis before machining, collected in Figures 20 and 21 indicate a rich amount of Ti, Al and V. In addition, the total of C and O significantly increased on the Ti surface after machining (Figure 22). Based on the data, the percentage of the Ti, Al and V decreased that are mostly composted with oxygen and carbon in the air or EDM oil.

In the image of EDX analysis of NiTi SMA, a tungsten tool trace was observed on the surface as shown in Figure 23. The machining SMA with a tungsten electrode tool resulted in that trace of tungsten, which was also confirmed from the analysis of composition after machining, as shown in Table 9. Besides the tungsten, oxygen and carbon were also present on the surface after machining. These elements came from the air surrounding the lab and dielectric oil. Generally, the carbon is created from the decomposition of the hydrocarbon dielectric oil during EDM machining. The amount of the oxygen came from the oxidation of the molten debris on the surface (See Figures 6, 7, 8 and 9).

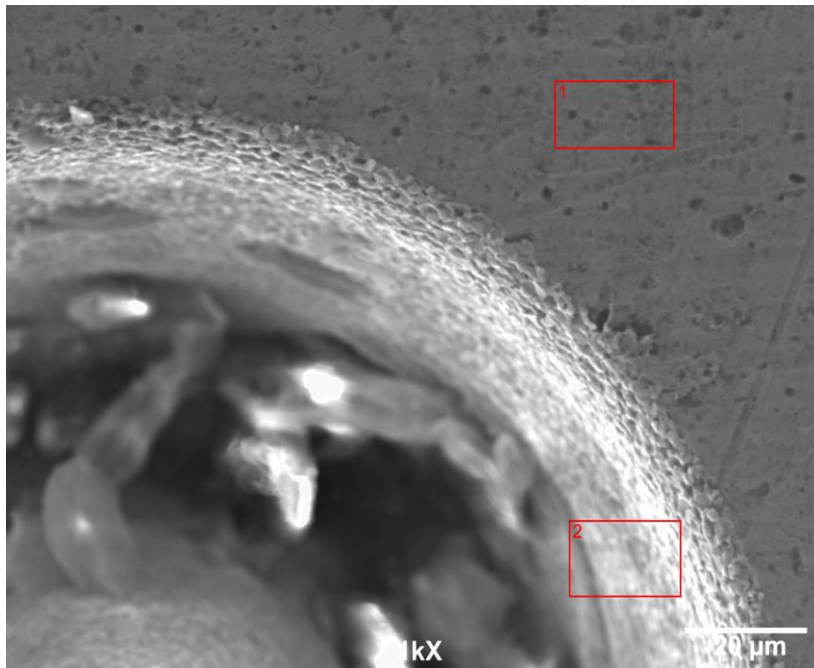


Figure 20. Single blind hole of Ti 1) before machining 2) after machining

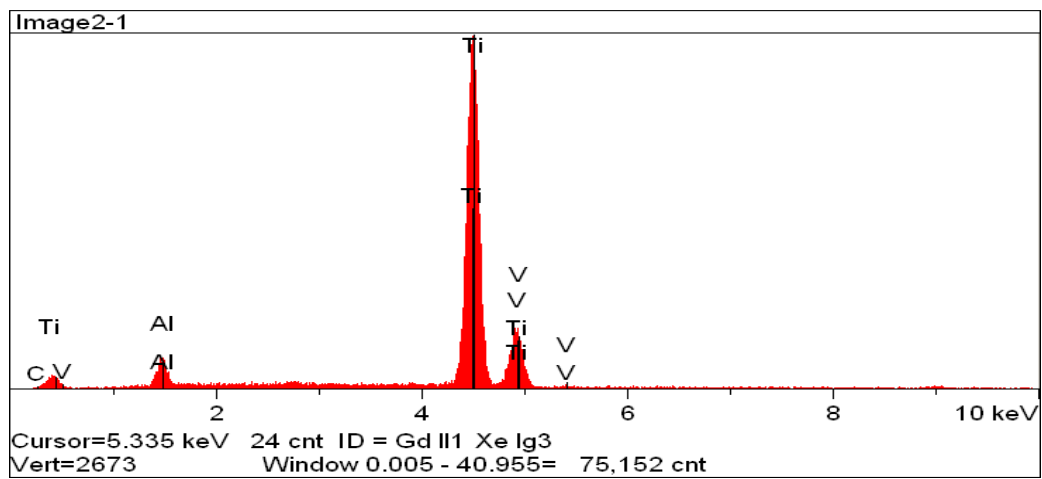


Figure 21. EDX analysis before machining (1)

Table 6

*Different materials on the Ti surface before machining (1)*

Elt.	Intensity	Error	Atomic	Conc
C	0.00	0.00	0.00	Wt%
O	0.00	0.00	0.00	Wt%
Al	198.79	9.34	5.48	Wt%
Ti	3365.49	88.05	91.64	Wt%
V	93.60	2.60	2.88	Wt%
		100.00	100.00	Wt%

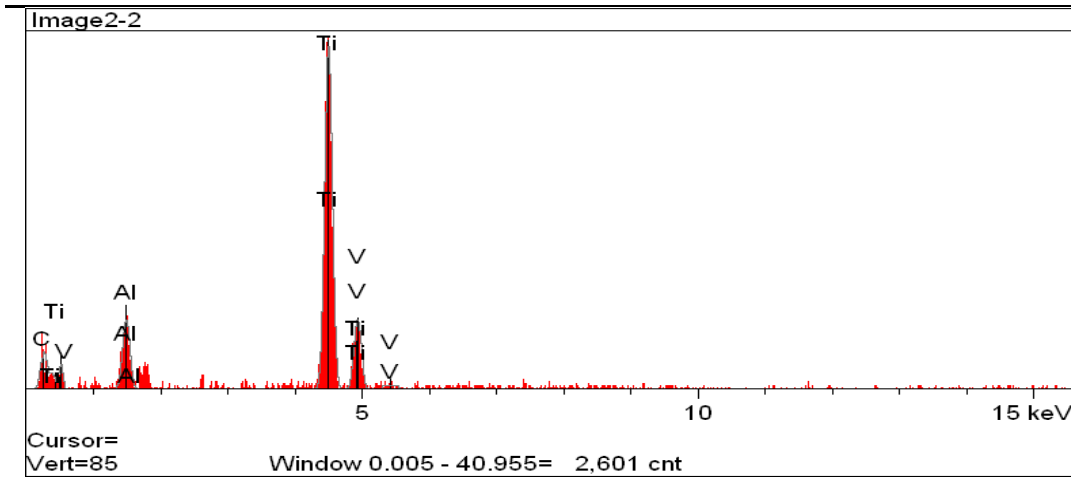


Figure 22. EDX analysis after machining (2)

Table 7

*Different materials on the Ti surface after machining (2)*

Elt.	Intensity	Error	Atomic	Conc
C	3.84	46.71	23.82	Wt%
O	0.71	18.90	12.83	Wt%
Al	7.47	7.64	8.75	Wt%
Ti	38.45	25.01	50.82	Wt%
V	2.52	1.75	3.78	Wt%
		100.00	100.00	Wt%

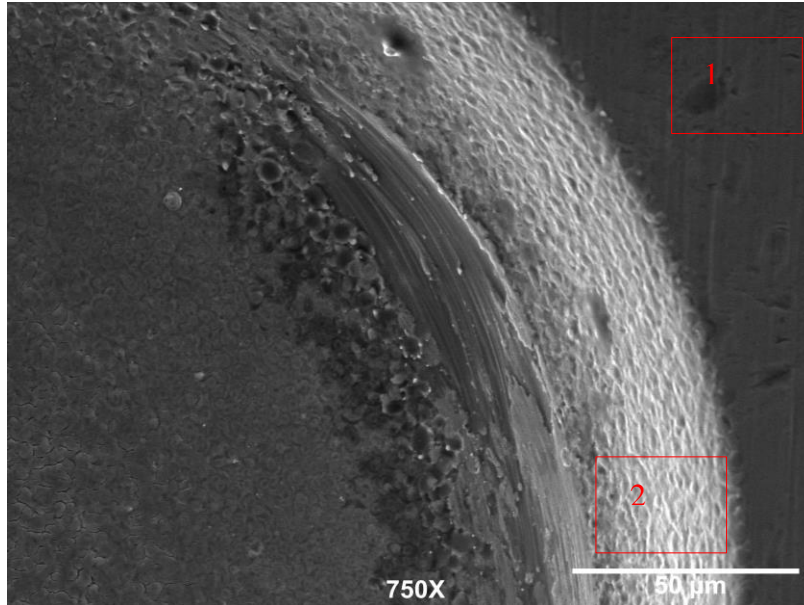


Figure 23. Single blind hole of TiNi SMA 1) before machining 2) after machining

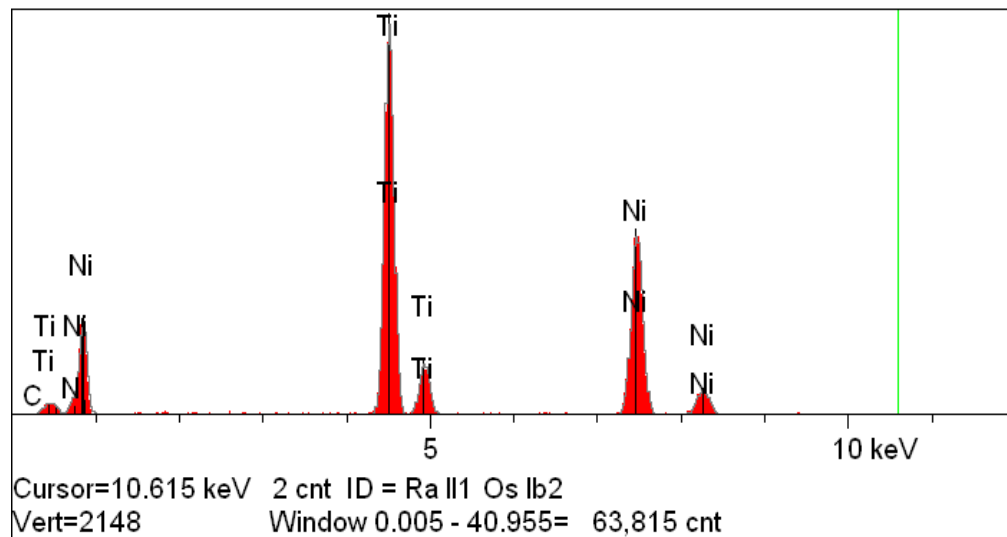
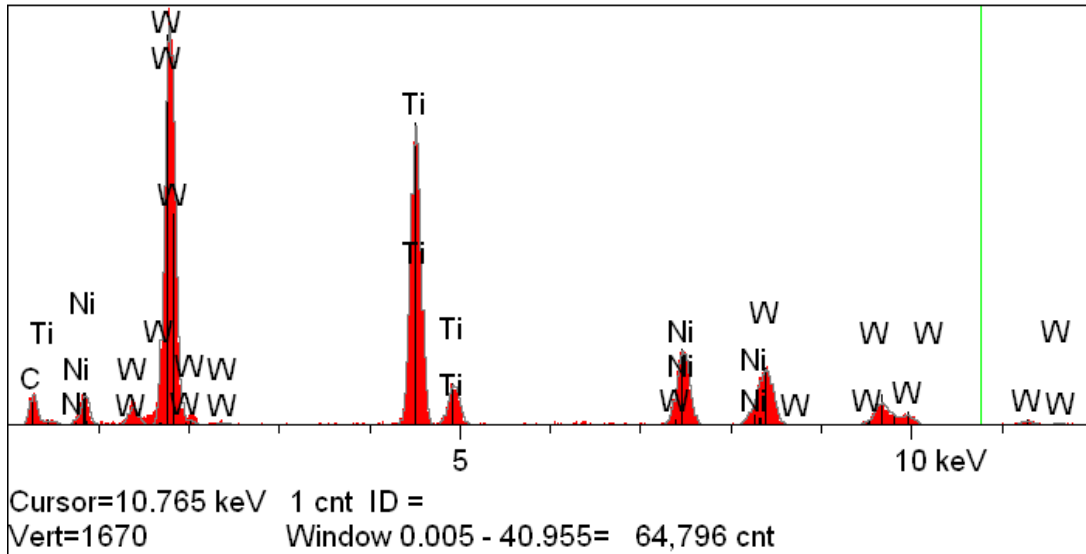


Figure 24. EDX analysis before machining (1)

Table 8

*Different materials on the SMA surface before machining (1)*

Elt.	Intensity	Error	Atomic	Conc
C	1.17	0.771	3.46	0.80
O	0.00	0.842	0.00	0.00
Ti	495.38	5.953	46.94	43.21
Ni	269.55	4.394	49.60	55.99
			100.00	100.00



*Figure 25. EDX analysis after machining (2)*



Table 9

*Different materials on the SMA surface after machining (2)*

Elt.	Intensity (c/s)	Error 2-sig	Atomic%	Conc
C	22.68	1.643	39.36	12.85
O	0.43	0.567	11.65	8.98
Ti	285.78	4.663	20.82	12.23
Ni	82.07	2.682	12.79	13.83
W	68.87	2.503	15.38	52.11
			100.00	100.00

### **X-Ray Diffraction (XRD) Analysis**

Besides the SEM and EDX analysis, the XRD analysis was employed to find changes on the EDM surface and compounds formed after machining. According to the XRD result in Figure 26, the machined surfaces of both workpieces changed during the EDM machining. The presence of oxygen, carbon and tungsten was due to the evidence of the tungsten wear rate and dielectric liquid. The XRD system helps the researcher to find the alloy layer formed on the workpiece surface and alloy changes because of the penetration of other materials into the workpiece surface. According to Figure 26, various phases and materials beside Ni and Ti have been seen in NiTi SMA such as NiTiO<sub>3</sub> and NiO metal oxides. In the XRD analysis of the Ti workpiece, the compositions of different materials have been seen such as TiO<sub>2</sub> and WO<sub>2</sub>. The reason for the existence of these different compounds is that the mechanical and physical properties changed on the surface during machining.

The highest peak is Ti in the Ti-6Al-4V workpiece that occurred at 2 $\theta$  values of 65.0. In the SMA analysis, there is not any significantly rich Ni, which can be harmful for

the human body. The most common components in the NiTi SMA were  $\text{NiTiO}_3$  and  $\text{WO}_2$  after machining. The surface quality depended on a dielectric liquid and machining parameters and conditions.

The XRD analysis was done two times (regular speed and low speed, twenty four hours of X-Ray), because one unknown peak was found for NiTi SMA during the first time analysis using regular speed. After using low speed, the XRD analysis showed a rich W on the surface. In the center of a hole in the surface, the electrode tool left an amount of tungsten due to tool wear phenomenon.

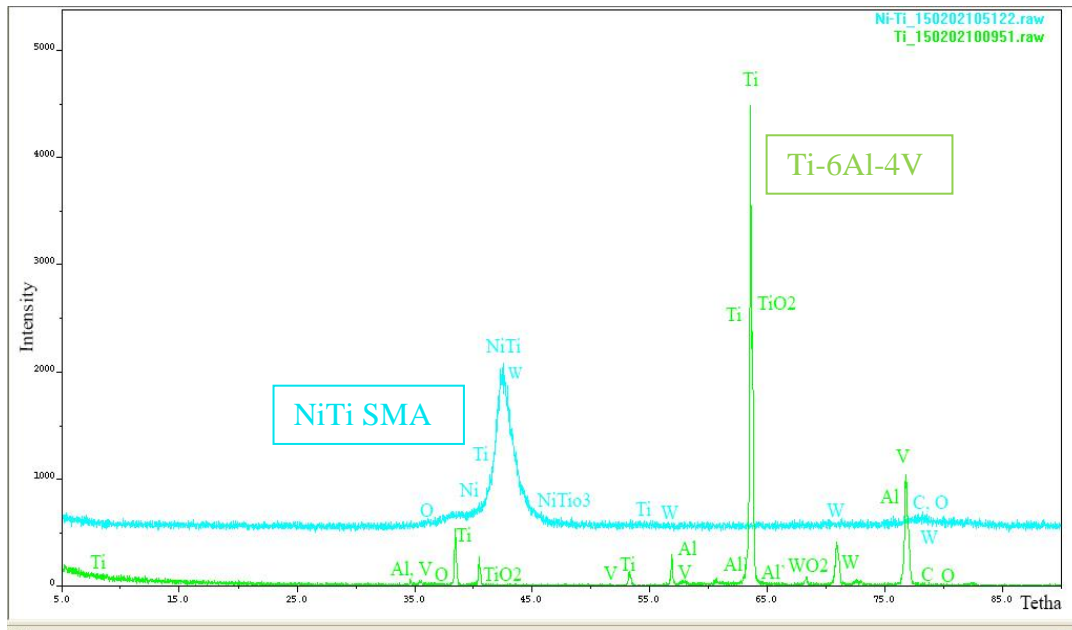


Figure 26: XRD analysis of NiTi SMA and Ti-6Al-4V alloys.

### 5\*5 Array of Blind Holes

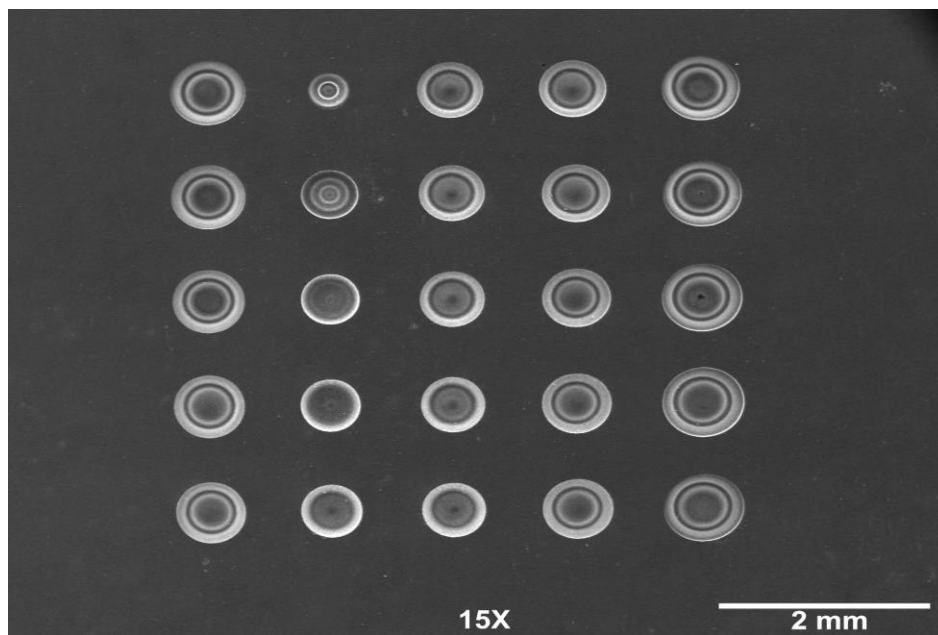
One of the most important usages of micro-EDM is the fabrication of array of features in hard materials. For example, in aerospace engineering micro holes commonly use different sizes of nozzles in micro-jet cooling devices and ink-jet nozzle (Moses, 2014; Zeng et al., 2012). An array of 5\*5 micro-holes was performed for both Ti and

NiTi SMA workpieces. This experiment was done with a 0.3 mm (300 micron) tungsten carbide tool electrode using the same parameters.

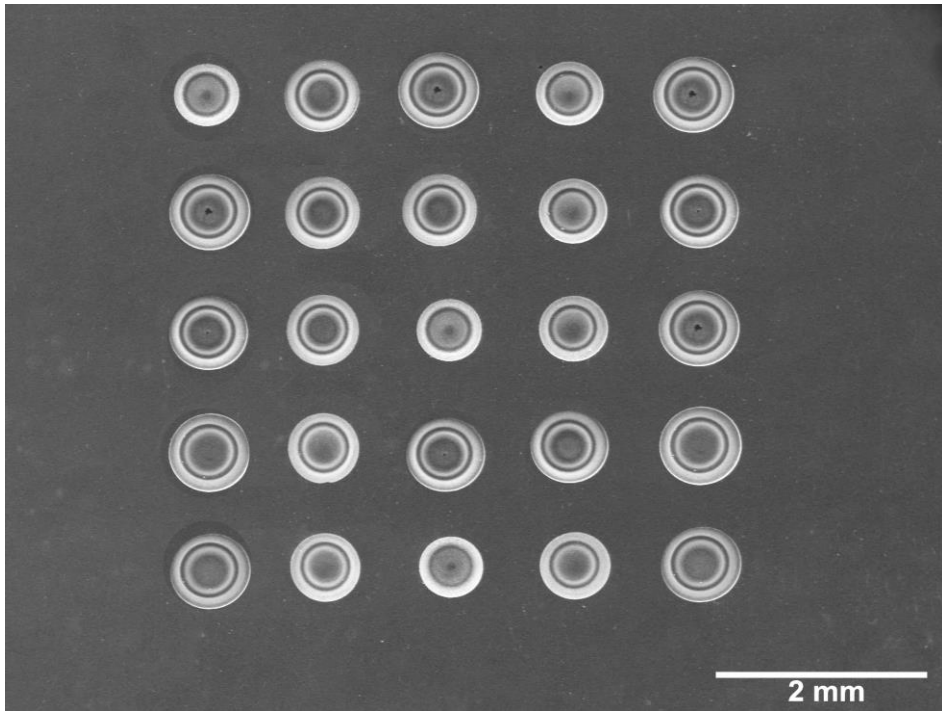
Based on the SEM picture shown in Figure 27, each blind hole has a different size and surface during EDM of Ti because various factors influenced the machining performance. For example, in Figure 27, the holes in the right hand of the picture have different size and quality compared to those in left hand side. This is because the right hand holes were created at the beginning and have a smoother surface with the acceptable size. At the beginning of the machining, the tool electrode was new, but experienced more tool wear as machining progressed. When electrode wear occurred during the machining, it affected both the dimensional and surface quality of the micro features. Therefore, Figure 27 also indicates comparatively higher electrode wear during machining of Ti alloy. On the other hand, micro holes in NiTi SMA are smoother and of higher dimension accuracy compared to those of Ti workpiece. Although, both NiTi and Ti alloys have high density and corrosion resistance, the observation indicated that the SMA has the better surface finish than Ti (Figure 28).

Micro molding in titanium and nickel alloys is a common manufacturing technique used extensively at present because of the advantages of low cost, good biocompatibility and high impact strength (Park et al., 2011). Using a specific micro-pattern could be useful for micro molding as well as other tasks such as writing or lettering in different materials (Moses, 2014). The lettering experiment was done with both Ti and NiTi SMA workpieces by machining the “H” letters, which were observed with SEM. Figures 29 and 30 show that the machined surface of NiTi SMA has less debris particles than that of Ti. This pattern was machined using the same conditions with

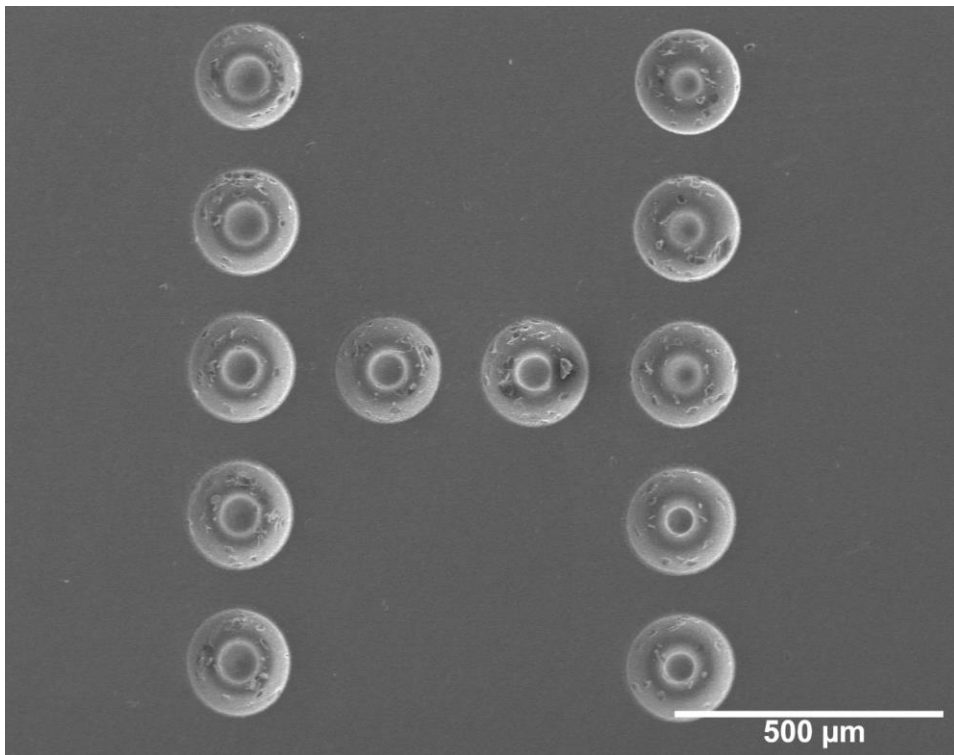
the tungsten electrode tool. Ten micro-holes were machined with 25  $\mu\text{m}$  depth and same parameter settings to compare the surface finish of two workpieces. The SEM images show that the holes on the NiTi SMA have better quality and surface. Because of the changing of NiTi SMA workpiece two times during the process, one mistake was observed on a hole after analyzing by SEM.



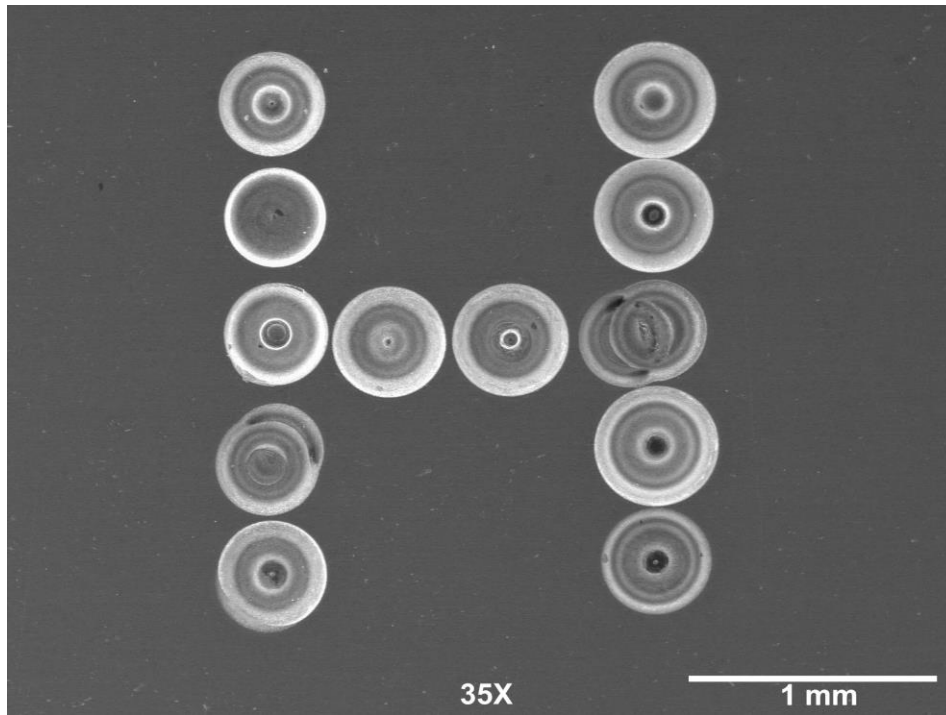
*Figure 27.* An array hole of Ti-6Al-4V



*Figure 28. An array hole of NiTi SMA*



*Figure 29. Machining of letter “H” of Blind Holes (Titanium)*



*Figure 30. Machining of letter “H” of Blind Holes (NiTi SMA)*

## **Part 2: Effect of Voltage, Capacitance and Rotation Speed on Machining Time**

In order to obtain the best efficiency of micro-EDM, the researcher examined the effect of different parameters on machining time for both Ti and NiTi workpieces. The operating parameters of micro-EDM that were considered were voltage, capacitance (PF) and rotation speed (revolutions per minute, RPM). The machining time was captured for machining a single hole for different parameter combinations. By changing these three important parameters, the machining time was analyzed. After capturing all the machining time data, the data were analyzed by plotting graphs of machining time versus each parameter. Different parameters have different material removal and machining time. The researcher created holes for each specific parameter setting as shown in Figures 31 to 36. The purpose of this step was to find the optimal parameter settings for surface finish and quality.

Results indicated that with increasing voltage, the machining time decreased in both workpieces. In addition, there is a pattern changing at 2000 RPM when the capacitance was 4700 PF. In this situation, the machining time significantly increased more than at 3500 RPM.

Generally, the machining time for NiTi SMA was more than Ti alloy with the same parameters. At 30 PF and 1000 PF, the machining time of both Ti and NiTi were nearly same, but for 4700 PF, the machining time of Ti was less than SMA.

Higher voltage influenced the machining time, because by increasing voltage, the amount of material removal increased and machining time decreased. Moreover, in higher voltages, more damage of the machined surface was observed. Higher voltage decomposed the dielectric fluid more and resulted in higher material removal. However, in higher temperature the amount of resolidification and recast layer also increased. This caused the researcher to select a comparatively lower voltage to reduce the amount of damage on the machined surface.

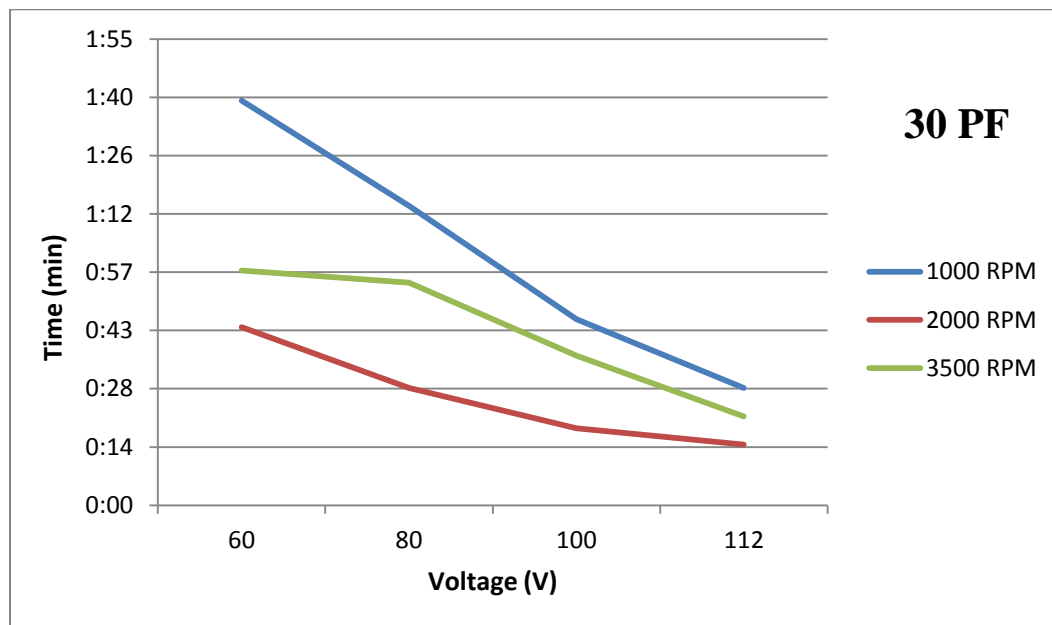


Figure 31. Machining time for NiTi SMA: 30 PF

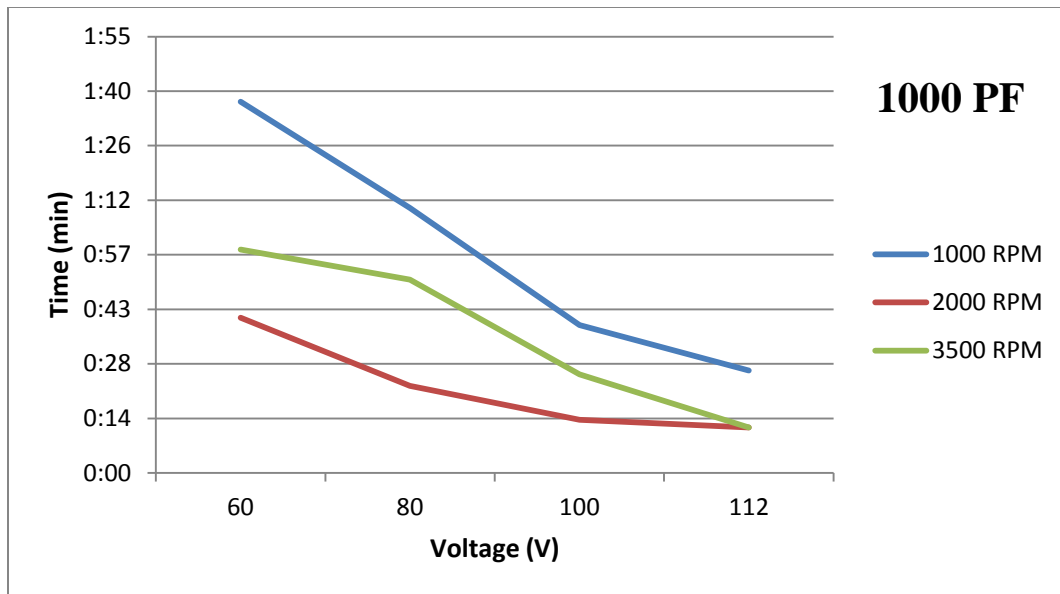


Figure 32. Machining time for NiTi SMA: 1000 PF

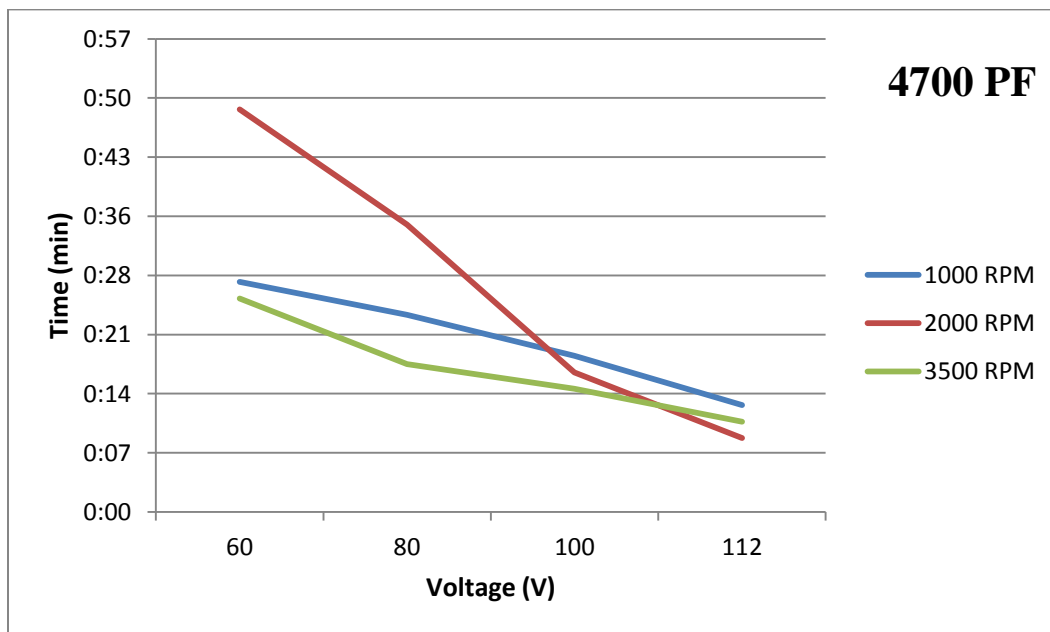


Figure 33. Machining time for NiTi SMA: 4700 PF



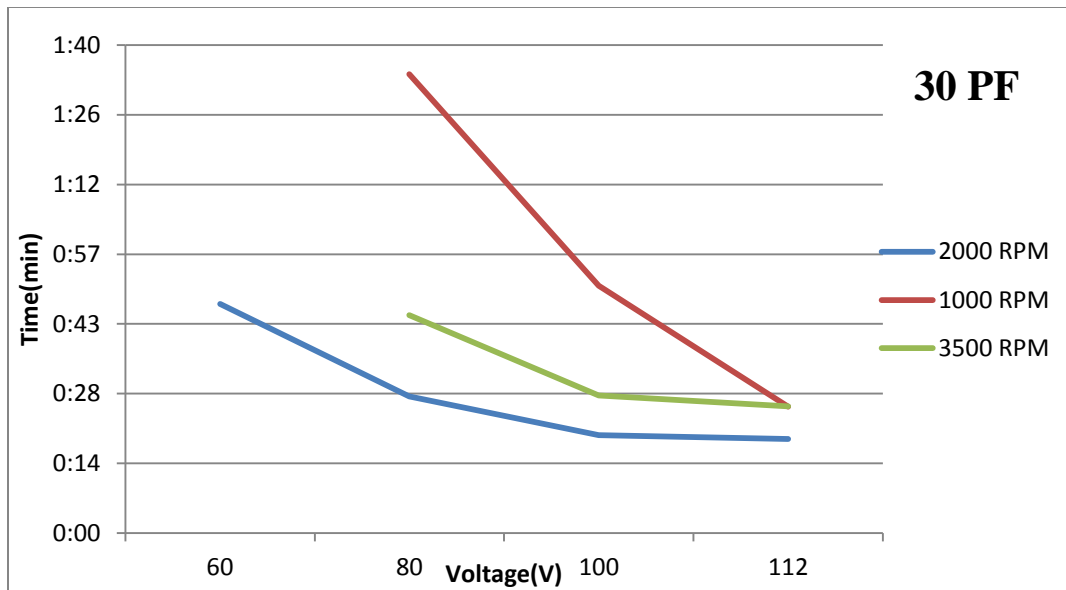


Figure 34. Machining time for Ti alloy: 30 PF

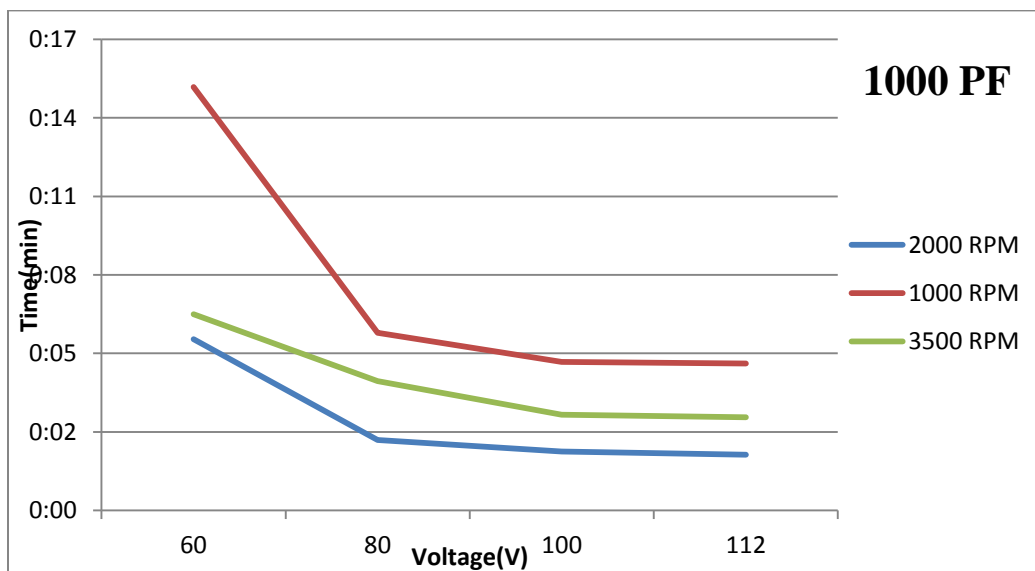


Figure 35. Machining time for Ti alloy: 1000 PF

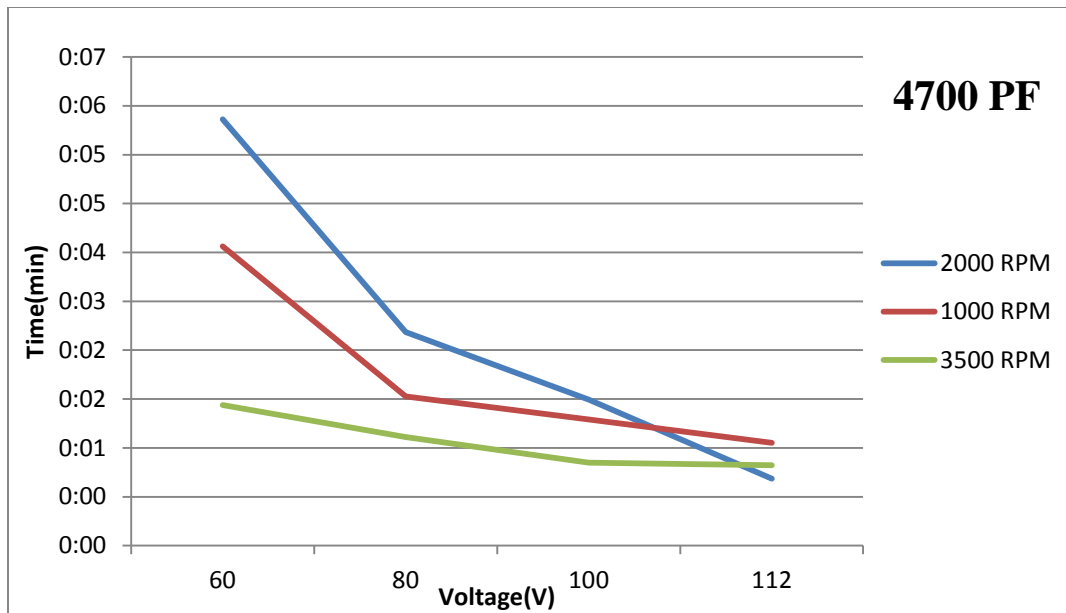


Figure 36. Machining time for Ti alloy: 4700 PF

## Conclusion

Titanium and Shape Memory alloys are extensively used in aerospace, biomedical and automotive industries due to their high specific strength (strength-to-weight ratio), superior mechanical and thermal properties, and excellent corrosion resistance. However, these alloys are commonly known as difficult-to-cut materials using conventional machining processes due to the reactivity of tool materials with these alloys, cutting speed limitation, chipping, and premature failure of the cutting tools. Different shapes of micro features were machined on the Ti-6Al-4V and NiTi SMA surfaces using an identified optimum parameter settings. The performances of both materials were compared based on the surface quality of micro features and machining time.

Based on the results from SEM, EDS and XRD analysis, the following conclusions were drawn:

- 1) Research Question 1: Does NiTi SMA have a better surface quality than Ti? Yes.

The amounts of the debris particles on the surface of Ti alloys were more compared to NiTi SMA. This result was observed from SEM analysis that showed the quality of machined surfaces. The machined surface of NiTi SMA was better than Ti because lower number of particles existed on the NiTi SMA surface. Both the workpieces are hard-to-cut materials but micro-EDM was able to successfully machine those materials.

- 2) Research Question 2: Do Ti and NiTi SMA have a biocompatible surface finish with micro-EDM? Yes. According to the results from XRD and EDS analyses, different compounds were found on the surface before and after machining. Because of the lab environment, the oxygen from the air transferred to the

machined surface after oxidation with workpiece materials. The dielectric fluid used also had an impact on surface quality. Because of the heat generation during the machining, the EDM oil was decomposed to other materials and released carbon on the machined surface. The amount of oxygen percentage on Ti workpiece was higher than NiTi SMA, which showed the better resistance of NiTi SMA. On the Ti surface there were various amount of  $\text{TiO}_2$  and O observed. The other factors that influenced machined surface quality was tool wear rate. The tungsten tool eroded during machining because of the heat generated. Thus, the trace of W was left on the NiTi SMA surface after machining using tungsten tool.

- 3) Research Question 3: Can micro-EDM successfully machine Ti and NiTi SMA? Yes. Different patterns such as blind hole, “H” lettering, and 5\*5 of array holes were successfully machined by micro-EDM. So, micro-EDM can be used for working with these hard-to-machine materials with minimal damage on the surface (based on the SEM pictures of NiTi SMA and Ti alloy).
- 4) Research Question 4: Is machining time of NiTi SMA higher than Ti? Yes. In this research, the effect of input parameters on machining time was considered. It was found that increasing voltage, the material removal increased and therefore, the machining time decreased. Based on the machining time of NiTi SMA and Ti graphs, the machining time of NiTi SMA was higher than Ti. Increasing voltage generated more heat, which created more recast layers and defects on the machined surface.
- 5) By increasing tool speed rotation (RPM), the machining time decreased except in one situation. The machining time unexpectedly increased in 2000 RPM more

than 1000 and 3500 RPM, when the capacitance was 4700 PF. Therefore, the voltage of 60 V, capacitance of 1000 PF and tool rotational speed of 3500 RPM were selected as optimum parameters for this study.

NiTi SMA and Ti alloy are commonly used in different applications such as aerospace and biomedical technologies because of their specific properties. Besides these value added properties, they have a major problem. They are commonly known as difficult-to-machine materials. Micro-EDM as one of the non-traditional technologies was used in this research. From the results from SEM images, the researcher concluded that micro-EDM can successfully machine NiTi SMA and Ti-6Al-4V hard-to-machine materials. These two materials are primarily used in biomedical industries as implants. The researcher attempted to investigate whether they have any harmful substances after machining for the human body. The EDX and XRD analysis were employed in order to find different elements and compositions on the machined surface. NiTi SMA was found to have better surface quality and fewer amounts of debris elements than the Ti alloy. The optimal parameters of this research were 60 V, 3500 RPM and 1000 PF.

### **Recommendation for future study**

Future studies need to focus on solving the problem that was addressed in this thesis. The EDX results for NiTi SMA and Ti alloy indicated traces of tungsten electrode tool on the surface. So, during the machining, there was significant amount of tool electrode wear, which needs to be considered in future studies. After machining of NiTi SMA and Ti alloy, the researcher found amounts of carbon on the surface because of the dielectric decomposition. Thus, future studies require providing a new liquid in order to have better surface quality and fewer amount of carbon on the surface.

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